A HANDLING QUALITIES INVESTIGATION OF CONVENTIONAL, RATE COMMAND/ATTITUDE HOLD, AND ATTITUDE COMMAND/ATTITUDE HOLD RESPONSE-TYPES IN THE PROBE AND DROGUE AIR REFUELING TASK

THESIS

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AFIT/GAE/ENY/94M-4

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Wright-Patterson Air Force Base, Ohio

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THESIS

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Master of Science in Aerospace Engineering

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Captain, USAF

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Preface

This report is the culmination of a one year research effort at the Air Force Institute of Technology (AFIT) and a five month longitudinal handling qualities investigation conducted as a Test Pilot School (TPS) test management project (TMP). I'm extremely grateful for the unique opportunity to not only research an area of interest to the flying qualities community, but to also actually conduct the flight testing.

Most of the flight test results were published in a technical letter report, AFFTC-TLR-93-38, to fulfill USAF TPS curriculum requirements. However, some pilot ratings and analysis were removed from early drafts of that report during technical coordination. Pilot rating variability is inevitable in any handling qualities investigation and this experiment was no exception. The challenge for the researcher is to identify the reasons for it. This report documents all the flight test results and provides more analysis of those results.

I would like to recognize several individuals whose talents and contributions made this research not only possible, but a truly rewarding experience. First, I'd like to thank my advisor, Dr. Brad Liebst. His advice lead to the selection of a handling qualities research project. I'm also deeply indebted to Mr. Dave Leggett of the Flight Dynamics Lab for sponsoring the project. He was instrumental in defining the research objectives and gathering the financial support to make it all happen.

I'm also deeply indebted to many people at Edwards Air Force Base, especially the other members of the HAVE GAS test team, Capt Don Watrous, Capt Dave Deary, and Capt Dan Sheridan. Their talents and hard work made the flight test planning, execution, and reporting go smoothly. I'd also like to thank LTC Dan Gleason and LTC Ron Johnston of the USAF TPS for their guidance. LTC Gleason provided valuable assistance throughout the entire joint AFIT/TPS program. LTC Johnston's personal involvement in the project assured

all the flight test assets came together at Patuxent River Naval Air Station on a three day holiday weekend. I'd also like thank Mrs. Mary Shafer and Mr. Ed Schneider of the NASA Dryden Flight Research Center. Mrs. Shafer's assistance and experience with handling qualities investigations were highly appreciated. Mr. Schneider's professional instruction in the F-18 Hornet was also highly appreciated. His experience brought both rookie project pilots up to speed in the probe and drogue air refueling task in minimum time.

I wish to thank several other flying qualities experts who provided advice and support for this project. Several individuals of Calspan Advanced Technology Center were involved to various degrees in the project. I'd like to thank Mr. Mike Parrag, Mr. John Ball, Mr. Arno Schelhorn, and Mr. Charles Chalk for their advice. Mr. Chalk's handling qualities experience was especially helpful early in the project. In particular, I'd like to thank Mr. Lou Knotts, Mr. Jeff Peer, and Mr. Eric Ohmit for their support. Mr. Knotts and Mr. Peer served as safety pilots during the inflight evaluations and their advice and handling qualities experience were invaluable. Mr. Ohmit programmed the flight control laws in the NT-33A and assisted with the handling qualities investigation. I'd also like to thank Mr. Dave Mitchell of Hoh Aeronautics for his advice and support through out the project.

I wish to thank many people at Patuxent River Naval Air Station for supporting the flight test program. CDR George Hill, LCDR Raymond Griffith, Lt Mark Andreas, Lt Sean Brennan, Lt Dennis Fitzgerald, Lt Steve Rauch, Lt Timothy Summers, Lt Jonathan Wilcox, PO Brian Barth, PO George Hoy, PO Tim Meyer, ENS Chris Kipp Mr. Rob Mattedi, Mr. Dave Wright, for the S-3A support. LCDR Steve Senteio, Lt Larry Eggbert, Mr. Jim Lewis, Mr. Cornelius Stripling for supporting flight test operations at the Naval TPS.

Finally, I'd like to thank my wife, Dee Dee, for her support throughout the joint AFIT/TPS program. Her sacrifices made it possible for me to realize my dreams. Thank you.

Michael J. Taschner

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List of Symbols

A	state matrix	as required
$\hat{A}$	state matrix	as required
$\tilde{A}$	state matrix	as required
a_z	z axis acceleration	$\mathrm{ft/sec^2}$
a_{z_p}	acceleration at the pilot station	$\mathrm{ft/sec^2}$
B	input matrix	as required
$\hat{B}$	input matrix	as required
$\tilde{B}$	input matrix	as required
b	reference span	ft
C	output matrix	as required
C_D	$\frac{D}{qS}$	dimensionless
C_{D_u}	$\frac{U}{2}\frac{\partial C_D}{\partial U}$	dimensionless
C_{D_α}	$\frac{\partial C_D}{\partial \alpha}$	1/rad
$C_{D_{\delta_e}}$	$\frac{\partial C_D}{\partial \delta_e}$	1/rad
C_L	$\frac{L}{qS}$	dimensionless
C_{L_h}	$\frac{L_h}{qS_h}$	dimensionless
C_{L_u}	$\frac{U}{2}\frac{\partial C_L}{\partial U}$	dimensionless
C_{L_α}	$\frac{\partial C_L}{\partial \alpha}$	1/rad
$C_{L_{\alpha_h}}$	$\frac{\partial C_{L_h}}{\partial \alpha}$	1/rad
$C_{L_{\delta_e}}$	$\frac{\partial C_L}{\partial \delta_e}$	1/rad
C_M	$\frac{M}{qSc}$	dimensionless
C_{M_q}	$\frac{\partial C_M}{\partial (qc/2U)}$	1/rad
C_{M_u}	$\frac{U}{2}\frac{\partial C_M}{\partial U}$	dimensionless
C_{M_α}	$\frac{\partial C_M}{\partial \alpha}$	1/rad

$C_{M_{\dot{\alpha}}}$	$\frac{\partial C_M}{\partial(\dot{\alpha}c/2U)}$	1/rad
$C_{M_{\delta_e}}$	$\frac{\partial C_M}{\partial \delta_e}$	1/rad
c	mean aerodynamic chord	ft
D	aerodynamic drag	lb
D	direct transmission matrix	as required
DB	Gibson dropback parameter	deg
Drb	STI dropback parameter	deg
F_{as}	aileron stick force, positive right	lb
F_{es}	elevator stick force, positive aft	lb
F_{rp}	rudder pedal force, positive for right pedal forward	lb
G	transfer function	as required
G	$C(sI-A)^{-1}B+D$, transfer function matrix	as required
G_i	command filter transfer function	as required
g	gravitational acceleration	ft/sec^2
h	altitude	ft
H_c	pressure altitude	ft
I	identity matrix	dimensionless
I_{xx}	moment of inertia about x axis	$slug-ft^2$
I_{yy}	moment of inertia about y axis	$slug-ft^2$
I_{zz}	moment of inertia about z axis	$slug-ft^2$
I_{xz}	product of inertia in x-z body axis plane	$slug-ft^2$
j	$\sqrt{-1}$	dimensionless
K	gain	as required
K_{ff}	VSS feed forward gain	deg/deg
K_{pf}	command gain	deg/sec/lb
K_q	loop gain	deg/deg/sec
K_q	δ_e/q	deg/deg/sec

$K_{q_{out}}$	q feedback gain	deg/deg/sec
K_α	δ_e/α	deg/deg
$K_{\alpha_{out}}$	α feedback gain	deg/deg
K_θ	θ/F_{es} transfer function gain	deg/sec/lb
K'_θ	θ/δ_{es} transfer function gain	deg/sec/in
L	aerodynamic lift	lb
l_h	distance between cg and horizontal tail aerodynamic center	ft
M	Mach number	dimensionless
m	mass	slugs
M_q	$\frac{\rho SUc^2}{4I_{yy}}(C_{M_q})$	1/sec
$\tilde{M}_q$	$M_q + M_{\dot{\alpha}}$	1/sec
$\hat{M}_q$	$M_q + M_{\dot{\alpha}}$	1/sec
M_u	$\frac{\rho SUc}{I_{yy}}(C_M + C_{M_u})$	1/ft−sec
$\hat{M}_u$	$M_u + \frac{M_{\dot{\alpha}}}{U_0} Z_u$	1/ft−sec
M_w	$\frac{\rho SUc}{2I_{yy}}(C_{M_\alpha})$	1/ft - sec
$M_{\dot{w}}$	$\frac{\rho Sc^2}{4I_{yy}}(C_{M_{\dot{\alpha}}})$	1/ft
M_α	$\frac{\rho SU^2c}{2I_{yy}}(C_{M_\alpha})$	$1/\text{sec}^2$
$\hat{M}_\alpha$	$M_\alpha + M_{\dot{\alpha}} \frac{Z_\alpha}{U_0}$	$1/\text{sec}^2$
$M_{\dot{\alpha}}$	$\frac{\rho SUc^2}{4I_{yy}}(C_{M_{\dot{\alpha}}})$	1/sec
M_{δ_e}	$\frac{\rho SU^2c}{2I_{yy}}(C_{M_{\delta_e}})$	$1/\text{rad}-\text{sec}^2$
$\hat{M}_{\delta_e}$	$M_{\delta_e} + \frac{M_{\dot{\alpha}}}{U_0} Z_{\delta_e}$	$1/\text{rad}-\text{sec}^2$
n	load factor	dimensionless
n_{z_p}	normal acceleration at the pilot station	g
$n_{z_{cg}}$	normal acceleration at the center of gravity	g
Q	$180/\pi$, transformation matrix	deg/rad
Q_0	$R_0 \tan\Phi_0$	deg/sec
q	$\frac{1}{2}\rho V^2$, dynamic pressure	lb/ft^2

q	pitch rate	deg/sec
q_c	pitch rate command	deg/sec
q_e	pitch rate error	deg/sec
q_h	dynamic pressure at the horizontal tail	lb/ft^2
q_{peak}	peak pitch rate	deg/sec
q_{ss}	steady-state pitch rate	deg/sec
R	yawing velocity	deg/sec
R	permutation matrix	dimensionless
S	surface area of wing	ft^2
S_h	surface area of horizontal tail	ft^2
s	Laplace operator	1/sec
T	transformation matrix	as required
t	time	sec
T_q	superaugmented pitch loop lead time constant	sec
T_{sp_1}	stable RSS fighter short period pole time constant	sec
T_{sp_2}	unstable RSS fighter short period pole time constant	sec
T_{wo}	washout time constant	sec
T_{θ_1}	low frequency attitude lead time constant	sec
T_{θ_2}	high frequency attitude lead time constant	sec
u	x-axis velocity component (small perturbation)	ft/sec
u	input (control) vector	rad
u_g	x-axis gust velocity (small perturbation)	ft/sec
U	component of V along x-axis	ft/sec
U_0	trim component of V along x-axis	ft/sec
V	velocity	ft/sec
V_T	true velocity	ft/sec
v	input (control) vector	rad

W	weight	pounds
W	z-axis velocity component	ft/sec
w	z-axis velocity component (small perturbation)	ft/sec
w	state vector	as required
w_g	z-axis gust velocity (small perturbation)	ft/sec
x	state vector	as required
x_a	distance from cg, positive forward	ft
X_u	$\frac{\rho SU}{m}(-C_D - C_{D_u})$	1/sec
X_w	$\frac{\rho SU}{2m}(C_L - C_{D_\alpha})$	1/sec
X_α	$\frac{\rho SU^2}{2m}(C_L - C_{D_\alpha})$	ft/sec^2
X_{δ_e}	$\frac{\rho SU^2}{2m}(-C_{D_{\delta_e}})$	$ft/rad-sec^2$
Z_u	$\frac{\rho SU}{m}(-C_L - C_{L_u})$	1/sec
Z_w	$\frac{\rho SU}{2m}(-C_{L_\alpha} - C_D)$	1/sec
Z_α	$\frac{\rho SU^2}{2m}(-C_{L_\alpha} - C_D)$	ft/sec^2
Z_{δ_e}	$\frac{\rho SU^2}{2m}(-C_{L_{\delta_e}})$	$ft/rad-sec^2$
z	state vector	as required
α	angle-of-attack (small perturbation)	deg
α_0	trim angle-of-attack	deg
δ_{as}	aileron stick deflection, positive right	in
δ_{es}	elevator stick deflection, positive aft	in
δ_{rp}	rudder pedal deflection, positive for right forward	in
δ_a	$\left(\delta_{a_R} - \delta_{a_L}\right)/2$, total aileron deflection	deg
δ_{a_R}	right aileron deflection, positive trailing edge down	deg
δ_{a_L}	left aileron deflection, positive trailing edge down	deg
δ_e	elevator deflection, positive trailing edge down	deg
δ_p	pilot command	deg/sec
δ_r	rudder deflection, positive trailing edge left	deg

ε	downwash angle	deg
ε	angle between principle axis and fuselage reference line	deg
Φ	bank angle	deg
Φ	phase angle	deg
Φ_0	trim bank angle	deg
Φ_M	phase margin	deg
γ	flight path angle (small perturbation)	deg
γ_0	trim flight path angle	deg
λ_p	phugoid mode eigenvalues	rad/sec
λ_{p_1}	stable RSS fighter phugoid pole	rad/sec
λ_{p_2}	unstable RSS fighter phugoid pole	rad/sec
π	pi	dimensionless
θ	pitch attitude angle (small perturbation)	deg
θ_0	trim pitch attitude angle	deg
ρ	density of air	lb/ft^3
τ	time constant	sec
τ_1	first order system lead time constant	sec
τ_2	first order system lag time constant	sec
τ_{p_θ}	phase delay	sec
ω	frequency	rad/sec
ω_{BW}	bandwidth	rad/sec
$\omega_{BW_{gain}}$	gain margin bandwidth	rad/sec
$\omega_{BW_{phase}}$	phase margin bandwidth	rad/sec
ω_{BW_θ}	pitch attitude bandwidth	rad/sec
ω_{BW_γ}	flight path bandwidth	rad/sec
ω_n	natural frequency	rad/sec
ω_p	phugoid natural frequency	rad/sec

ω_{sp}	short period natural frequency	rad/sec
ω'	effective natural frequency	rad/sec
ω_3	actuator natural frequency	rad/sec
ω_{180}	frequency where $\Phi = -180°$	rad/sec
ζ_n	damping ratio	dimensionless
ζ_p	phugoid damping ratio	dimensionless
ζ_{sp}	short period damping ratio	dimensionless
ζ'	effective damping ratio	dimensionless

List of Abbreviations and Acronyms

AAR	air-to-air refueling
ACAH	attitude command/attitude hold
ACM	air combat maneuvers
AFB	Air Force Base
AFFDL	Air Force Flight Dynamics Laboratory
AFFTC	Air Force Flight Test Center
AFIT	Air Force Institute of Technology
AFMC	Air Force Materiel Command
AFR	Air Force Regulation
AFSC	aircraft flight control system
AFWAL	Air Force Wright Aeronautical Laboratories
AGARD	Advisory Group for Aerospace Research and Development
AHC	aircraft handling characteristics
AIAA	American Institute of Aeronautics and Astronautics
ANSI	American National Standards Institute
APC	approach power compensator
AOA	angle-of-attack
ARS	air refueling store
CAL	Cornell Aeronautical Laboratory
CAP	control anticipation parameter
CAS	control augmentation system
C-H	Cooper-Harper
CR	contractor report
CSAS	command and stability augmentation system
cg	center of gravity
DAS	data acquisition system
DC	direct current
DFC	direct force control
DMS	Differential Maneuvering Simulator
DTIC	Defense Technical Information Center
dB	decibel
deg	degree(s)
EAP	Experimental Aircraft Program

EFA	European Fighter Aircraft
FBW	fly-by-wire
FCS	flight control system
FWATD	Force Warfare Aircraft Test Directorate
fps	feet per second
ft	feet
FTE	flight test engineer
GCGH	gamma command/gamma hold
GM	gain margin
HOS	higher order system
HQDT	handling qualities during tracking
HQR	handling qualities rating
HUD	head-up display
ICAS	International Council of the Aeronautical Sciences
in	inches
KIAS	knots indicated airspeed
KTAS	knots true airspeed
LAHOS	landing approach higher order system
LAMARS	Large Amplitude Multi-mode Aerospace Research Simulator
LaRC	Langley Research Center
LOES	low order equivalent system
lb	pound
M	Mach number
MAC	mean aerodynamic chord
MIL-SPEC	military specification
MIL-STD	military standard
MTE	mission task element
msec	millisecond
NAS	Naval Air Station
NASA	National Aeronautics and Space Administration
NATOPS	Naval Air Training and Operating Procedures Standardization
NAVAIR	Naval Air
NAWC	Naval Air Warfare Center
NAWCAD	Naval Air Warfare Center, Aircraft Division
NOE	nap-of-the-earth
PA	pressure altitude

PIO	pilot induced oscillation
PIOR	pilot induced oscillation rating
PLC	Public Limited Company
PM	phase margin
psf	pounds per square foot
psi	pounds per square inch
RCAH	rate command/attitude hold
RCP	recorder control panel
RSS	relaxed static stability
rad	radian
SAS	stability augmentation system
SCAS	stability and control augmentation system
STI	Systems Technology Incorporated
STOL	short takeoff and landing
sec	second
TAF	Tactical Air Force
TIFS	Total Inflight Simulator
TLR	technical letter report
TMP	test management project
TN	technical note
TPR	transient peak ratio
TPS	Test Pilot School
TR	technical report
TTFCS	task tailored flight control system
USAF	United States Air Force
USN	United States Navy
V	volts
VMS	Visual/Motion Simulator
VTOL	vertical takeoff and landing
VSS	variable stability system
WL	Wright Laboratory
WSO	weapons systems officer

Abstract

This investigation examines the suitability of conventional, rate command/attitude hold (RCAH) and attitude command/attitude hold (ACAH) response-types for the probe and drogue air refueling task. Longitudinal handling qualities data were collected using the NT-33A variable stability aircraft to support the development of a mission-oriented flying qualities military standard (MIL-STD).

Data from a 1974 handling qualities investigation involving conventional response-types in the probe and drogue air refueling task were analyzed using the Bandwidth and Dropback criterions to determine trends and correlation with pilot commentary. Flight control laws were then developed to achieve twelve new superaugmented configurations and to replicate two of the previous conventional configurations. The NT-33A analog variable stability system (VSS) simulated a relaxed static stability (RSS) fighter and the NT-33A programmable digital flight control computer simulated the desired response-types (RCAH, ACAH, and conventional). The pitch attitude and flight path bandwidths for the superaugmented aircraft were chosen to investigate a range of bandwidths spanning the Level 1 and Level 2 handling qualities bandwidths from the previous investigation. Pitch acceleration per pound of stick input was held constant among all but one of the configurations and so control sensitivity varied with pitch attitude bandwidth.

The handling qualities of the fourteen configurations were evaluated for suitability in the probe and drogue air refueling task during eight flight test sorties. Data consisted of pilot commentary, handling qualities ratings using the Cooper-Harper rating scale, pilot induced oscillation (PIO) tendency ratings, and turbulence ratings. Most RCAH configurations were suitable for the task. Handling qualities of RCAH extended bandwidth and conventional response-types were similar and, in general, superior to the RCAH

response-types. An improperly mechanized trim system hindered the evaluation of the *desired* ACAH response-types. The basic characteristics of the ACAH response-type appeared favorable for the probe and drogue air refueling task and warrant further investigation. The Bandwidth criterion supplemented with frequency response based control sensitivity metrics can be used to predict handling qualities for small amplitude compensatory tracking tasks. Configurations with handling qualities deficiencies were characterized by any one of the following: excessive gain at the pitch attitude and flight path bandwidths, excessive phase delay, low bandwidth, or a gain margin limited pitch attitude bandwidth.

A HANDLING QUALITIES INVESTIGATION OF CONVENTIONAL, RATE COMMAND/ATTITUDE HOLD, AND ATTITUDE COMMAND/ATTITUDE HOLD RESPONSE-TYPES IN THE PROBE AND DROGUE AIR REFUELING TASK

I. Introduction

1.1 Motivation

The acceptance of the F-16 Fighting Falcon into the Tactical Air Force (TAF) marked a significant milestone in aviation history. This was the first of a new breed of operational aircraft to realize the performance advantages offered by a relaxed static stability (RSS) airframe coupled with a multiple-redundant full-authority fly-by-wire (FBW) flight control system (FCS). To the fighter pilot, the F-16 is not only highly maneuverable and extremely agile, it's also amazingly easy to fly. But the F-16 *has* to be easy to fly. The high demands of the single-seat fighter mission absolutely require an aircraft with superb flying qualities. On a typical F-16 sortie, the fighter pilot is not only flying the aircraft, he's clearing the flight path, maintaining formation, clearing the visual arena, monitoring the radar, monitoring the radio, monitoring the radar warning receiver for threat information, monitoring fuel status and engine performance, navigating, and updating the inertial navigation system, monitoring weapon status, to name just a *few.* All of this and more must be done skillfully to accomplish the real mission-getting into valid weapons parameters and employing ordnance. Prior to the F-16, this workload was usually split between the pilot and the weapon system officer (WSO). The pilot concentrated on flying while the WSO operated the avionics. Obviously, for one man to accomplish the mission by himself, the workload required to manually fly the aircraft has be reduced to a minimal level.

The F-16 is now joined by several other modern high performance operational aircraft such as the F-18 Hornet, Tornado, and Mirage 2000, as well as experimental aircraft such as the X-29A, FBW Jaguar, Experimental Aircraft Program (EAP), European Fighter Aircraft (EFA), and Rafale A Demonstrator. Like the F-16, each of these aircraft also utilize a full-authority FCS to modify the vehicle's dynamics so key dynamics of the effective aircraft as presented to the pilot depend primarily on the controller dynamics. Often the equivalent vehicle is of very high order and has dynamics that no longer correspond to those of a conventional aircraft, differing in kind as well as degree [MMJ84, p.2]. Recent advances in digital multi-mode FBW FCSs, now make it possible to go one step beyond stabilizing/controlling the aircraft to actually optimizing the aircraft/flight control system (AFCS) dynamics so the pilot has the best response characteristics (response-type) for each individual mission task rather than a composite average for the mission as a whole. Aircraft designers will undoubtedly incorporate this new flexibility into future fighters and design task tailored flight control systems (TTFCS) that achieve some *best* output response to the pilot's input, thereby minimizing the pilot's control-centered workload. In addition, TTFCSs may make it possible to accomplish entirely new tasks which are not possible with conventional aircraft dynamics. Finally, a TTFCS may provide effective vehicle dynamics that are insensitive to a wide variety of different pilot techniques. However, a key question needs answering. What response-type does a pilot prefer for a given task? While the new flight control technology can provide mission-task-oriented flying qualities characteristics bordering on absolute optimum, someone must be able to define just what that is [MJM86, p.531].

1.2 Objectives

The overall objective of this project was to examine the suitability of three different response-types for accomplishing a selected mission task element (MTE), in this case, probe

and drogue air refueling. Flying qualities engineers from the Flight Dynamics Lab are interested in handling qualities research to support a future mission-oriented flying qualities military standard (MIL-STD). The current flying qualities military standard, MIL-STD-1797A, contains little design guidance for other than conventional response-types and little specification compliance criterion for performance of operational tasks.

The probe and drogue air refueling task was selected as the MTE for several reasons. First, probe and drogue air refueling is a militarily important operational task. The Navy and Marine Corp's ability to *simultaneously* refuel several fighters from one strategic tanker or buddy refuel from another tactical aircraft during Operation Desert Storm using probe and drogue air refueling generated considerable interest within the Air Force. At the time this project was getting started, several studies were underway to determine the feasibility of retrofitting USAF fighters to have a probe and drogue air refueling capability. Although the decision was made not to retrofit USAF fighters, a probe and drogue air refueling capability for the F-16 was recently demonstrated.

There were other good reasons for the probe and drogue air refueling task. Several recent handling qualities experiments have investigated the suitability of various response-types for the flared landing task, but little work has been accomplished for other tasks. Limited conventional response-type probe and drogue air refueling handling qualities data for were available for analysis and the USAF NT-33A variable stability aircraft could again be modified with an air refueling probe to collect more data with other response-types.

Finally, probe and drogue air refueling is essentially a small amplitude compensatory tracking task and allows for linear flight control system design and analysis. The flight control system design techniques taught at both AFIT and USAF TPS were directly applicable.

The response-types evaluated were selected after a review of the literature. The rate command/attitude hold (RCAH) response-type was selected because several aircraft currently use this response-type for air refueling. MIL-STD-1797A design and specification

guidance for this response-type is limited. The attitude command/attitude hold (ACAH) response-type was selected because it potentially offers a high level of precision in pitch and flight path control and was untested in the task. Two conventional response-types from the previous investigation were selected for reevaluation. One configuration served as a baseline "good" conventional aircraft and the other offered another look at a high dropback configuration.

1.3 Methodology

A simple methodology was used to accomplish the above objectives.

1. A literature review was accomplished to determine what work in this area had been previously accomplished. Major topics of interest were longitudinal equations of motion, response-type characteristics, handling qualities metrics, flight control system design, and handling qualities experiment design.

2. Configurations from a previous Calspan handling qualities investigation that involved probe and drogue air refueling were modeled in SIMULINK™ and analyzed with the Bandwidth and Dropback criterions. This analysis was compared with the flight test results (pilot commentary, handling qualities ratings, pilot induced oscillation (PIO) tendency ratings) to determine correlation and trends.

3. Preliminary work was accomplished with simple models to determine the feasibility of competing flight control system architecture's. One simple architecture was selected for detailed flight control systems analysis and handling qualities predictions. Several refinements to this architecture were made prior to flight test. Refinements included updating the NT-33A model to the best available and modeling the variable stability system (VSS) filters. Additionally, two conventional response-type configurations from the previous probe and drogue air refueling experiment were remodeled for flight testing.

4. All configurations were flight tested in the probe and drogue air refueling task. Data collected during flight test included pilot commentary, handling qualities ratings using the Cooper-Harper rating scale, PIO tendency ratings, and turbulence ratings.

5. The flight test data were analyzed to determine trends and correlation with the handling qualities predictions.

1.4 Assumptions and Limitations

Several assumptions and simplifications were made to keep the designs as simple as possible and yet still achieve the desired response-types. All flight control system designs were point designs based on linearized longitudinal equations of motion[1] valid for one flight condition and a medium fuel state. Sensitivity of the flight control system gains to changes in flight condition and fuel state were not evaluated. Consequently, gain scheduling was not used. Any changes to the equations of motion necessary to account for the addition of the air refueling probe to the NT-33A were assumed negligible and were not made. Although it is possible to model a hybrid digital and analog FCS using SIMULINK, all configurations were modeled in the continuous time domain. First order filters were used to model the anti-aliasing filters. Computational time delay was modeled with a first order Padé approximation. Turn compensation was not incorporated into any of the designs and consequently the task was accomplished in wings level flight. Gust responses were not evaluated analytically and flight conditions were adjusted to minimize the effects of turbulence. None of these assumptions and limitations restrict the results of this longitudinal handling qualities investigation, however, they are considerations necessary in the *complete* design of a flight control system.

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[1]The only exception was a nonlinear center stick breakout force.

II. Literature Review

2.1 Introduction

The starting point for this project was a literature review. Major topics of interest were equations of motion, response-type characteristics, handling qualities metrics, flight control system design, and handling qualities experiment design. The first three of these areas will be discussed here as background information. The last two areas will be discussed later during the flight control system design (Chapter 4) and handling qualities experiment design (Chapter 5).

Most of the literature reviewed was written by handling qualities specialists from Arvin Calspan Advanced Technology Center, and Systems Technology Incorporated (STI). Calspan reports were primarily documentation of inflight handling qualities research performed in the Total Inflight Simulator (TIFS) or the NT-33A variable stability aircraft. STI reports involved not only empirical studies of previous handling qualities experiments, but also analytical studies which were tested in ground-based motion simulators such as the Air Force Wright Aeronautical Laboratories (AFWAL) Large Amplitude Multi-mode Aerospace Research Simulator (LAMARS) or the NASA Langley Research Center (LaRC) Differential Maneuvering Simulator (DMS) or Visual/Motion Simulator (VMS).

Much of the material was published in the 80's and early 90's and is recent enough to not be in MIL-STD-1797A.

2.2 Longitudinal Dynamics

2.2.1 Sign Conventions The sign convention used (in this study) for control surface deflections conforms with the AIAA recommended practice [AIAA92, p.35]. This convention, based on the right hand rule, is widely recognized and fairly widely used in the literature. This sign convention is summarized in Table 2.1 and depicted in Figure 2.1.

Table 2.1. Sign Convention for Control Surface Deflections

Sign Convention for Control Surface Deflections			
Surface	Symbol	Sign	Direction[1]
Elevator	δ_e	+	trailing edge down
Aileron	δ_a	+	—
Rudder	δ_r	+	trailing edge left

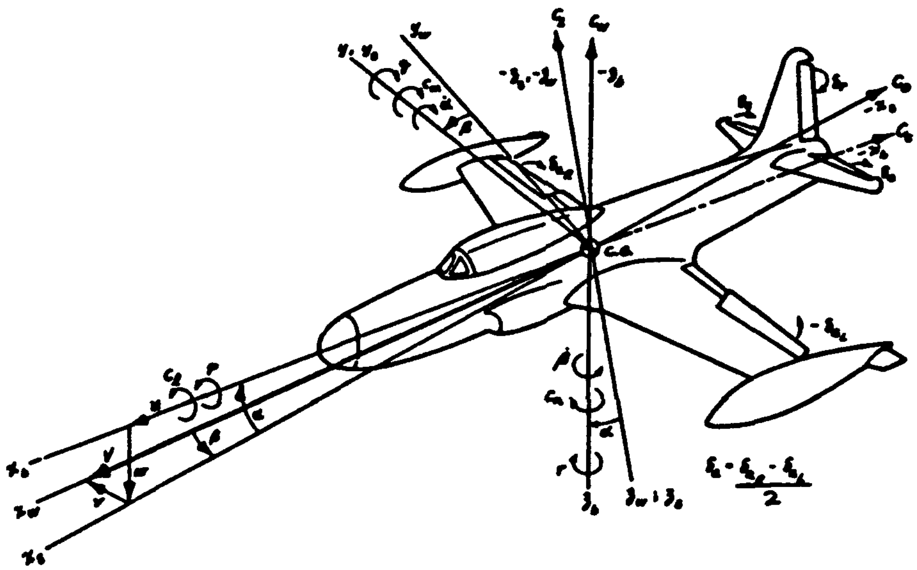

Figure 2.1. Sign Convention for Control Surface Deflections [HH70, p.114]

The sign convention for pilot control inputs (used in this study) conforms with that published in [HH70, p.xxvi]. Positive control inputs produce positive moments about all three axes. This convention is summarized in Table 2.2.

[1]The ailerons move in opposite directions. A positive deflection f - each aileron is trailing edge down and the total aileron deflection is a combination of the individual aileron deflections: $\delta_a = (\delta_{a_R} - \delta_{a_L})/2$.

Table 2.2. Sign Convention for Pilot Control Inputs

Sign Convention for Pilot Control Inputs			
Control	**Symbol**	**Sign**	**Direction**
Elevator Stick Force	F_{es}	+	aft
Elevator Stick Deflection	δ_{es}	+	aft
Aileron Stick Force	F_{as}	+	right
Aileron Stick Deflection	δ_{as}	+	right
Rudder Pedal Force	F_{rp}	+	right[2]
Rudder Pedal Deflection	δ_{rp}	+	right[2]

2.2.2 Three Degree of Freedom Equations of Motion The three degree of freedom, linearized longitudinal equations of motion for an aircraft are developed in [MAG73, p.203-307]. The equations are based on the following assumptions:

1. The airframe is a rigid body.
2. The earth is fixed in space.
3. The mass and mass distribution of the aircraft is constant.
4. The *XZ* plane is a plane of symmetry.
5. The disturbances from the steady flight conditions are small enough so that the sines and cosines of the disturbance angles are approximately the angles themselves and one, respectively, and so the products and squares of the disturbance quantities are negligible in comparison with the quantities themselves.
6. The aerodynamic trim forces are essentially symmetrical about the *XZ* plane, so there are no appreciable lateral forces or moments induced by longitudinal perturbed motions (u, w, q).
7. The flow is quasisteady.
8. Variations of atmospheric properties, such as density or speed of sound, are considered negligible for the small altitude perturbations of interest.

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[2]Right rudder pedal forward.

9. Effects associated with rotation of the vertical relative to inertial space are considered negligible; furthermore, the trim body axis pitching velocity, Q_0, is assumed to be zero.

10. $X_{\dot{w}} = X_q = Z_{\dot{w}} = Z_q = 0$.

11. In the steady flight condition, the flight path of the aircraft is horizontal, $\gamma_0 = 0$.

Under these assumptions the longitudinal equations of motion, referenced to stability axes, are [MAG73, p.298]

$$\begin{bmatrix} (s-X_u) & -X_w & g \\ -Z_u & (s-Z_w) & -U_0 s \\ -M_u & -(M_{\dot{w}}s+M_w) & s(s-M_q) \end{bmatrix} \begin{bmatrix} u \\ w \\ \theta \end{bmatrix} = \begin{bmatrix} X_{\delta_e} & -X_u & -X_w \\ Z_{\delta_e} & -Z_u & -Z_w \\ M_{\delta_e} & -M_u & -\left[\left(M_{\dot{w}} - \frac{M_q}{U_0}\right)s + M_w\right] \end{bmatrix} \begin{bmatrix} \delta_e \\ u_g \\ w_g \end{bmatrix} \tag{2.1}$$

where

$$s\theta = q \tag{2.2}$$

and (inertial terms of Z equation of Eqn 2.1)

$$a_z = \dot{w} - U_0 q = -U_0(\dot{\gamma}) = -\ddot{h} \tag{2.3}$$

The auxiliary relations, Eqn 2.2 and Eqn 2.3, are needed to convert the motion variables of Eqn 2.1 to the quantities sensed by flight instruments such as rate gyros, accelerometers, and altimeters. If wind gusts are neglected, then Eqn 2.1 reduces to

$$\begin{bmatrix} (s-X_u) & -X_w & g \\ -Z_u & (s-Z_w) & -U_0 s \\ -M_u & -(M_{\dot{w}}s+M_w) & s(s-M_q) \end{bmatrix} \begin{bmatrix} u \\ w \\ \theta \end{bmatrix} = \begin{bmatrix} X_{\delta_e} \\ Z_{\delta_e} \\ M_{\delta_e} \end{bmatrix} [\delta_e] \tag{2.4}$$

Although Eqn 2.4 can be modeled in SIMULINK, it's easier to work with a state-space representation. Switching from the Laplace domain to the time domain gives the following state-space representation

$$\begin{bmatrix} \dot{w} \\ \dot{\theta} \\ \dot{q} \\ \dot{u} \end{bmatrix} = \begin{bmatrix} Z_w & 0 & U_0 & Z_u \\ 0 & 0 & 1 & 0 \\ (M_w + M_{\dot{w}} Z_w) & 0 & (M_q + M_{\dot{w}} U_0) & (M_u + M_{\dot{w}} Z_u) \\ X_w & -g & 0 & X_u \end{bmatrix} \begin{bmatrix} w \\ \theta \\ q \\ u \end{bmatrix} + \begin{bmatrix} Z_{\delta_e} \\ 0 \\ (M_{\delta_e} + M_{\dot{w}} Z_{\delta_e}) \\ X_{\delta_e} \end{bmatrix} [\delta_e] \tag{2.5}$$

Finally, substituting

$$\begin{aligned} w &= U_0 \alpha \\ X_w &= \frac{X_\alpha}{U_0} \\ M_w &= \frac{M_\alpha}{U_0} \\ M_{\dot{w}} &= \frac{M_{\dot{\alpha}}}{U_0} \end{aligned} \tag{2.6}$$

in Eqn 2.5 gives

$$\begin{bmatrix} \dot{\alpha} \\ \dot{\theta} \\ \dot{q} \\ \dot{u} \end{bmatrix} = \begin{bmatrix} Z_w & 0 & 1 & \frac{Z_u}{U_0} \\ 0 & 0 & 1 & 0 \\ (M_\alpha + M_{\dot{\alpha}} Z_w) & 0 & (M_q + M_{\dot{\alpha}}) & (M_u + M_{\dot{w}} Z_u) \\ X_\alpha & -g & 0 & X_u \end{bmatrix} \begin{bmatrix} \alpha \\ \theta \\ q \\ u \end{bmatrix} + \begin{bmatrix} \frac{Z_{\delta_e}}{U_0} \\ 0 \\ (M_{\delta_e} + M_{\dot{w}} Z_{\delta_e}) \\ X_{\delta_e} \end{bmatrix} [\delta_e] \tag{2.7}$$

Eqn 2.7 is the form of the aircraft equations of motion used during the preliminary design studies of this project. The longitudinal dimensional stability derivatives (stability axis system) are defined and related to nondimensional stability derivatives as described in Table 2.3.

Table 2.3. Longitudinal Dimensional Stability Derivatives (Stability Axis System) [MAG73, p.294]

Longitudinal Dimensional Stability Derivatives (Stability axis system)			
Quantity	Dimensional		Nondimensional
	Definition	Unit	
X_u	$\frac{1}{m}\frac{\partial X}{\partial u}$	$\frac{1}{\text{sec}}$	$\frac{\rho SU}{m}(-C_D - C_{D_u})$[3]
X_α	$\frac{1}{m}\frac{\partial X}{\partial \alpha}$	$\frac{\text{ft}}{\text{sec}^2}$	$\frac{\rho SU^2}{2m}(C_L - C_{D_\alpha})$
X_{δ_e}	$\frac{1}{m}\frac{\partial X}{\partial \delta_e}$	$\frac{\text{ft}}{\text{rad-sec}^2}$	$\frac{\rho SU^2}{2m}(-C_{D_{\delta_e}})$
Z_u	$\frac{1}{m}\frac{\partial Z}{\partial u}$	$\frac{1}{\text{sec}}$	$\frac{\rho SU}{m}(-C_L - C_{L_u})$[4]
Z_w	$\frac{1}{m}\frac{\partial Z}{\partial w}$	$\frac{1}{\text{sec}}$	$\frac{\rho SU}{2m}(-C_{L_\alpha} - C_D)$
Z_{δ_e}	$\frac{1}{m}\frac{\partial Z}{\partial \delta_e}$	$\frac{\text{ft}}{\text{rad-sec}^2}$	$\frac{\rho SU^2}{2m}(-C_{L_{\delta_e}})$
M_u	$\frac{1}{I_{yy}}\frac{\partial M}{\partial u}$	$\frac{1}{\text{ft-sec}}$	$\frac{\rho SUc}{I_{yy}}(C_M + C_{M_u})$
M_α	$\frac{1}{I_{yy}}\frac{\partial M}{\partial \alpha}$	$\frac{1}{\text{sec}^2}$	$\frac{\rho SU^2c}{2I_{yy}}(C_{M_\alpha})$
$M_{\dot{w}}$	$\frac{1}{I_{yy}}\frac{\partial M}{\partial \dot{w}}$	$\frac{1}{\text{ft}}$	$\frac{\rho Sc^2}{4I_{yy}}(C_{M_{\dot{\alpha}}})$
$M_{\dot{\alpha}}$	$\frac{1}{I_{yy}}\frac{\partial M}{\partial \dot{\alpha}}$	$\frac{1}{\text{sec}}$	$\frac{\rho SUc^2}{4I_{yy}}(C_{M_{\dot{\alpha}}})$
M_q	$\frac{1}{I_{yy}}\frac{\partial M}{\partial q}$	$\frac{1}{\text{sec}}$	$\frac{\rho SUc^2}{4I_{yy}}(C_{M_q})$
M_{δ_e}	$\frac{1}{I_{yy}}\frac{\partial M}{\partial \delta_e}$	$\frac{1}{\text{rad-sec}^2}$	$\frac{\rho SU^2c}{2I_{yy}}(C_{M_{\delta_e}})$

Prior to flight test, a best available state-space description of the USAF NT-33A variable stability aircraft was obtained and used for the final designs. This body axes state-space description was of the form

[3]The thrust gradient terms are neglected here in the interest of symmetry and consistency.

[4]For $C_{L_u} = 0$, as in subsonic flight, and $C_L = W/(\rho U^2 S/2)$, as in trimmed flight for $\gamma_0 = 0$, $Z_u = -2g/U_0$.

$$\begin{bmatrix}\dot{\alpha}\\ \dot{\theta}\\ \dot{q}\\ \dot{u}\end{bmatrix}=\begin{bmatrix} Z_w & -\frac{g}{U_0}\sin\theta_0 & 1 & \frac{Z_u}{U_0}\\ 0 & 0 & 1 & 0\\ (M_\alpha+M_{\dot{\alpha}}Z_w) & -gM_{\dot{w}}\sin\theta_0 & (M_q+M_{\dot{\alpha}}) & (M_u+M_{\dot{w}}Z_u)\\ X_\alpha & -g\cos\theta_0 & -W_0 & X_u\end{bmatrix}\begin{bmatrix}\alpha\\ \theta\\ q\\ u\end{bmatrix}+\begin{bmatrix}\frac{Z_{\delta_e}}{U_0}\\ 0\\ (M_{\delta_e}+M_{\dot{w}}Z_{\delta_e})\\ X_{\delta_e}\end{bmatrix}[\delta_e]$$

(2.8)

where Eqn 2.2 still holds and Eqn 2.3 becomes (body axes)

$$a_z=\dot{w}-U_0q+(g\sin\theta_0)\theta \tag{2.9}$$

The stability derivatives in Eqn 2.8 are now referenced to a body axis system other than the stability axes. The stability derivative transformation relationships between body axes and stability axes are discussed in Appendix A. Eqn 2.8 was derived in a similar manner to the derivation of Eqn 2.7 starting with the Laplace domain equations of motion given in [Tep69, p.C-1].

2.2.3 Two Degree of Freedom Equations of Motion This study is primarily concerned with the short term response of fighter type aircraft. The short term response (short period response) is characterized primarily by changes in angle of attack and pitch attitude, with little change in forward airspeed. By assuming the variation in forward velocity is zero, Eqn 2.7 simplifies to

$$\begin{bmatrix}\dot{\alpha}\\ \dot{\theta}\\ \dot{q}\end{bmatrix}=\begin{bmatrix} Z_w & 0 & 1\\ 0 & 0 & 1\\ (M_\alpha+M_{\dot{\alpha}}Z_w) & 0 & (M_q+M_{\dot{\alpha}})\end{bmatrix}\begin{bmatrix}\alpha\\ \theta\\ q\end{bmatrix}+\begin{bmatrix}\frac{Z_{\delta_e}}{U_0}\\ 0\\ (M_{\delta_e}+M_{\dot{w}}Z_{\delta_e})\end{bmatrix}[\delta_e] \tag{2.10}$$

Note θ and q decouple and θ can be removed leaving

$$\begin{bmatrix}\dot{\alpha}\\ \dot{q}\end{bmatrix}=\begin{bmatrix} Z_w & 1\\ (M_\alpha+M_{\dot{\alpha}}Z_w) & (M_q+M_{\dot{\alpha}})\end{bmatrix}\begin{bmatrix}\alpha\\ q\end{bmatrix}+\begin{bmatrix}\frac{Z_{\delta_e}}{U_0}\\ (M_{\delta_e}+M_{\dot{w}}Z_{\delta_e})\end{bmatrix}[\delta_e] \tag{2.11}$$

Eqn 2.11 will be used in Chapter 4 to determine realistic values for stability derivatives (M_α, $M_{\dot{\alpha}}$, M_q) to simulate a RSS fighter.

2.3 Flight Control System Evolution

The previous section described the equations of motion for a conventional aircraft. However, the task-tailoring of vehicle dynamics today is primarily accomplished by the flight control system. In an effort to better understand the reasons for augmenting an aircraft's dynamics, it's worthwhile to review the evolution of the jet fighter flight control system. Much of this background information is from [MAP90, p.14-15].

2.3.1 Conventional Aircraft America's first generation jet fighters were relatively simple conventional aircraft with very limited performance by today's standards. The simplest of these aircraft incorporated reversible, mechanical flight control systems consisting of cables, pushrods, bellcranks, etc.. The pilot felt the airloads on the control surfaces (feedback) and this helped limit his tendency to over control the aircraft. Higher performing aircraft used power-boosted, reversible flight control systems somewhat analogous to power steering used in cars today. The pilot had direct command of the control surfaces, but controlled the aircraft response indirectly through the aircraft dynamics. No vehicle output feedbacks were used (except by the pilot).

2.3.2 Stability Augmentation Systems By the late 50's, the second generation jet fighters, capable of supersonic flight, became operational. The push for higher performance dictated the use of hydraulic actuators to position the control surfaces. Since this irreversible system gives the pilot no feedback, an artificial feel system had to be included so the aircraft would not be over-controlled (and subsequently over-stressed). Higher performance also required fundamental changes in the aircraft shape such as thin swept surfaces (with associated poorer lift curve slopes), smaller all-movable tails, area-rule fuselages, etc.. These changes often resulted in handling qualities deficiencies that were

corrected by limited-authority stability augmentation systems (SAS). Aircraft modal characteristics were improved by feedback of selected aircraft responses to the control actuators. The SAS altered, but did not add, significant FCS dynamics (other than the feel system) and the pilot still primarily commanded control surface deflections directly and the aircraft response indirectly. The aircraft was typically designed to have good handling qualities at flight conditions representative of the primary mission and *acceptable* handling qualities elsewhere.

2.3.3 Command and Stability Augmentation Systems The 70's saw the introduction of third generation jet fighters. Small light-weight reliable computers and sensors were incorporated into full-authority command and stability augmentation systems (CSAS). Added FCS dynamics between the control stick and control surfaces made it possible to vary the response to a pilot input independently of the modal (aircraft) dynamics. The pilot directly commanded aircraft response variables (subject to limitations on bandwidth and control authority) not actual control surface deflections. For instance, The F-16 sidestick controller commands normal acceleration longitudinally and roll rate laterally over a wide range of the flight envelope (cruise gains). Both responses were recognized as important to the fighter pilot when performing the fighter mission.

The CSAS not only stabilizes the aircraft, it also provides desirable response-types and Level 1 handling qualities over a much wider range of the flight envelope. Often, substantial logic is employed in the flight control system to produce the desired response-types.

Another important FCS feature was the capability for carefree handling through the use of FCS limiters. Pilot's could now use bang-bang type control inputs while maneuvering against an adversary without worrying about over-stressing the aircraft or departing controlled flight.

2.3.4 Task-Tailored Flight Control Systems The TTFCS is really an extension of CSAS. A TTFCS (usually a digital multi-mode FBW FCS) allows the pilot to switch modes so as to directly command the response variable deemed appropriate for the task. Of course,

the fundamental question of TTFCS design is just what response variable does the pilot prefer to command for a given task.

Third generation fighters such as the F-16 already incorporate very limited capability TTFCSs. The F-16 for instance, changes from primarily a g command response-type (cruise gains) to primarily a RCAH response-type for landing. Whether these two response-types are optimum response-types for air combat and power approach and flared landing, respectively is very debatable.

An excellent summary of existing TTFCSs is given in [MMHJ87, p.5-9]. Both [MAM90] and [MAP90] document recent task tailoring efforts for ultra precision approach and landing systems and enhanced fighter maneuverability, respectively. Both of these studies involved considerable analysis and manned simulations of several response-types in either the NASA LaRC VMS or DMS. Some of the response-types tested were very unconventional. For instance the $\kappa-\tau$ control, a form of direct force control (DFC), was an attempt to allow the pilot to directly shape the maneuver trajectory independently of speed [MAP90, p.10-12]. With these response-types the pilot commanded curvature longitudinally and torsion laterally.

2.4 Response-Types

The response of a highly augmented aircraft to a pilot input depends on the nature of the feedbacks and feedforwards used in the FCS. The intent of defining response-types, however, is to catalog generic input/output characteristics rather than to define the FCS structure [Hoh88, p.1]. Some common response-types currently in use are conventional or AOA command, g command, rate command/attitude hold (RCAH), and attitude command/attitude hold (ACAH). Other response-types such as flight path command/flight path hold (GCGH), flight path rate command/flight path hold (GDCGH), and $\kappa-\tau$ control have been tested in ground based motion simulators.

The generic characteristics of the three response-types flight tested in this study are discussed below. Most of this material is from [Hoh88, p.2-4], [AGA91, p.22-25] and [HM86, p.30-44]. Generic frequency response amplitude asymptotes and time histories for conventional, RCAH, and ACAH response-types are shown in Figure 2.2. The corresponding approximate transfer functions for attitude, flight path, and AOA to a pitch control input are given in Table 2.4.

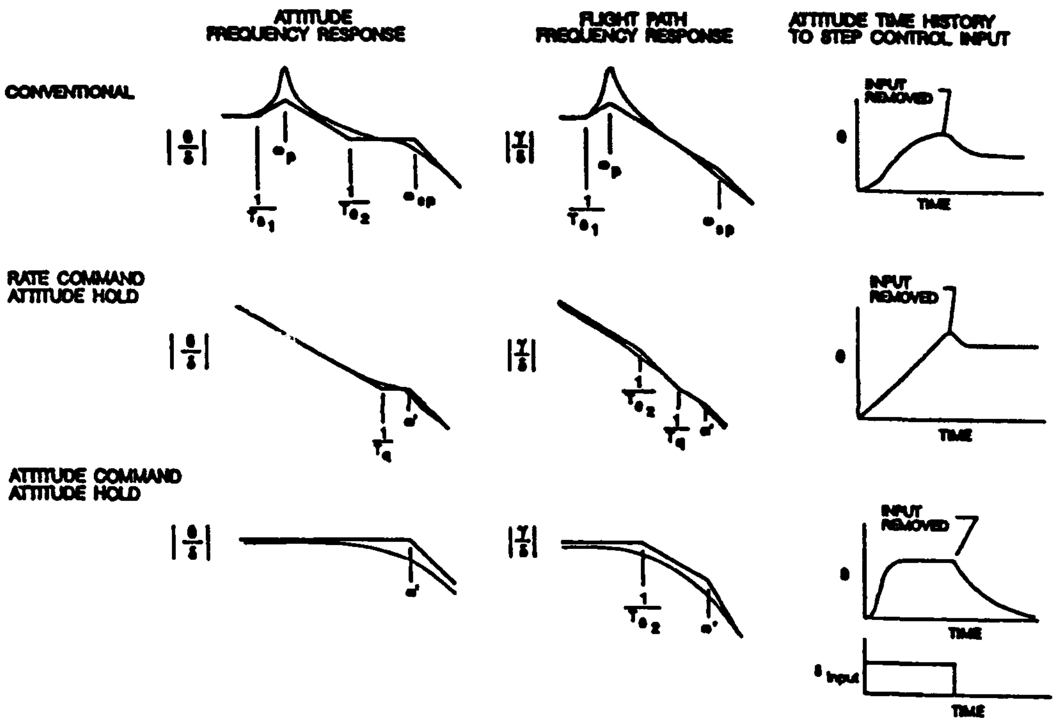

Figure 2.2. Generic Characteristics of Conventional, RCAH, and ACAH Response-Types [AGA91, p.24]

The important characteristics of these three response-types as they pertain to precision flight path control are discussed in more detail in the following subsections.

Table 2.4. Approximations for Attitude, Flight Path, and AOA to Pitch Control Input [HM86, p.36][3,4]

Approximations for Attitude, Flight Path, and AOA to Pitch Control Input			
Response-Type	θ/δ_{es}	γ/δ_{es}	α/δ_{es}
Conventional	$\frac{M_{\delta_e}(1/T_{\theta_1})(1/T_{\theta_2})}{[\zeta_p,\omega_p][\zeta_{sp},\omega_{sp}]}$	$\frac{M_{\delta_e} 1/T_{\theta_2}(1/T_{\theta_1})}{[\zeta_p,\omega_p][\zeta_{sp},\omega_{sp}]}$	$\frac{M_{\delta_e}}{[\zeta_{sp},\omega_{sp}]}$
RCAH	$\frac{K_q M_{\delta_e}(1/T_q)}{(0)[\zeta',\omega']}$	$\frac{K_q M_{\delta_e} 1/T_{\theta_2}(1/T_q)}{(0)(1/T_{\theta_2})[\zeta',\omega']}$	$\frac{K_q M_{\delta_e}(1/T_q)[\zeta_p,\omega_p]}{(0)(1/T_{\theta_1})(1/T_{\theta_2})[\zeta',\omega']}$
ACAH	$\frac{K_\theta M_{\delta_e}}{[\zeta',\omega']}$	$\frac{K_\theta M_{\delta_e} 1/T_{\theta_2}}{(1/T_{\theta_2})[\zeta',\omega']}$	$\frac{K_\theta M_{\delta_e}[\zeta_p,\omega_p]}{(1/T_{\theta_1})(1/T_{\theta_2})[\zeta',\omega']}$

2.4.1 Conventional Response-Type It's possible to achieve a conventional response-type from any configuration by feeding back pitch-rate and AOA, assuming adequate elevator control power. There are several important observations to be made regarding the generic characteristics of the conventional response-type for precision flight path control.

The short period and phugoid modes are well separated and easily identified. The phugoid mode is typically lightly damped, with an oscillation that occurs at constant AOA. The flat region of the θ/δ_{es} frequency response between $1/T_{\theta_2}$ and ω_{sp} leads to pitch-rate overshoot in the time domain (step elevator input). Augmenting the short period frequency increases this flat stretch and the pitch rate overshoot. Too much augmentation results in excessive dropback.

The γ/δ_{es} frequency response is K/s over a long stretch between the phugoid mode and the short period mode. The flight path response lags the attitude response by 90° at

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[3]Notation: $K_q, K_\theta, M_{\delta_e}, 1/T_{\theta_2} \rightarrow$ Gains, $\left(\frac{1}{T}\right) \rightarrow \left(s+\frac{1}{T}\right)$, $[\zeta,\omega] \rightarrow \left[s^2+2\zeta\omega+\omega^2\right]$

[4]The factor $1/T_{\theta_2}$ was missing from the conventional response-type γ/δ_{es} transfer function in [HM86] and was added here.

frequencies much above $1/T_{\theta_2}$ and is in phase with the attitude response at frequencies much below $1/T_{\theta_2}$. The following approximation applies

$$\frac{\gamma(s)}{\theta(s)} \cong \frac{1}{T_{\theta_2}s+1} \tag{2.12}$$

A low value of $1/T_{\theta_2}$ will lead to a large lag between θ and γ. The γ/δ_{es} frequency response is not affected by $1/T_{\theta_2}$ because pitch rate overshoot increases exactly proportional to a decrease in $1/T_{\theta_2}$. This is a result of the above mentioned flat stretch between $1/T_{\theta_2}$ and ω_{sp} in the θ/δ_{es} frequency response. This region is increased as $1/T_{\theta_2}$ is decreased, resulting in a compensating effect (i.e., the lack of flight path response to an attitude change is exactly compensated by a more rapid initial attitude response). This characteristic is unique to the conventional response-type and indicates the need for pitch-rate overshoot depends on the magnitude of $1/T_{\theta_2}$. A more fundamental and direct approach would be to concentrate on the need for a K/s γ/δ_{es} frequency response in the region of piloted crossover.

It is important to understand that a K/s response implies that two conditions must be satisfied: the amplitude plot should have a slope of −20 dB/decade, and the phase should be −90°. An excellent way to determine the extent of the region of K/s is to note where the phase curve departs from approximately −90°. It is also important to note that the crossover model predicts equally good pilot ratings for a pure gain controlled element in a continuous tracking task.

The α/δ_{es} frequency response is a constant amplitude at all frequencies below the short period frequency. The conventional response-type is essentially an AOA command response-type. The response to a step stick input is essentially a second order response in AOA.

The parameter $1/T_{\theta_2}$ is directly dependent on the aircraft lift-curve slope, C_{L_α}, and is related to the control anticipation parameter (CAP) specification parameter n/α as follows

$$\frac{n}{\alpha} \cong \frac{U_0}{g} \frac{1}{T_{\theta_2}} \tag{2.13}$$

2.4.2 Rate Command/Attitude Hold Response-Type **There are important differences between the conventional response-type and the RCAH response-type for precision flight path control.**

The flat region of the θ/δ_{es} frequency response is no longer defined by the lift curve slope (i.e. $1/T_{\theta_2}$) but by the augmentation zero $1/T_q$.

The γ/δ_{es} frequency response changes from K/s to K/s^2 (between $1/T_{\theta_2}$ and $1/T_q$, when $1/T_q >> 1/T_{\theta_2}$). In this case, poor handling qualities can be expected for tasks requiring direct and therefore precise control of flight path such as precision landing, air refueling, close formation flying, etc..

The AOA time response to a step stick input looks like either a step or a ramp depending on whether the γ/δ_{es} frequency response in the region of crossover is K/s (conventional response-type like), or K/s^2 (RCAH). The shape of the AOA time response is an indicator of the γ/δ_{es} frequency response characteristics in the region of crossover.

It is important to note that the fundamental pitch attitude and flight path responses are significantly different for the conventional response-type and the RCAH response-type. It is therefore *not* appropriate to apply the lower order equivalent system (LOES) criterion to the RCAH response-type, since the LOES method is based on a conventional relationship between attitude and flight path. If $1/T_{\theta_2}$ is approximately equal to $1/T_q$, the response-type becomes conventional like in the region of piloted crossover. However, the phugoid mode may be completely suppressed due to the pitch-rate feedback which is not characteristic of a conventional response-type.

2.4.3 Attitude Command/Attitude Hold Response-Type **The generic characteristics of the ACAH response-type are dramatically different from either conventional or RCAH response-types.**

As the name implies, the θ/δ_{es} frequency response is constant out to the "dominant mode", ω'. The response to a step stick input is essentially a second order response in θ.

The γ/δ_{es} frequency response has the desired K/s above $1/T_{\theta_2}$ and K below $1/T_{\theta_2}$. The response is clearly non-conventional, and a LOES approach to define parameters to plot on the CAP boundaries would be inappropriate.

The shape of the AOA time response is a step, with some overshoot. This is convenient in that it is possible to determine if the γ/δ_{es} frequency response has the right shape from an examination of the alpha time history to a step stick input.

The ACAH response-type has more phase margin at frequencies below $1/T_{\theta_2}$ than either the RCAH or conventional response-types, and hence might be expected to be the best response-type for precision flight path control.

2.4.4 Selecting the Proper Response-Type Studies have shown that certain generic response-types enhance the ability of the pilot to perform one or more elements of the aircraft mission. Therefore, an important first step in the design of a flight control system is to properly match the response-type to the MTE. An example of the advantages and disadvantages of several response-types for the precision landing MTE is given in Table 2.5.

In many cases, the selection of a response-type which is not the best one for the task produces acceptable, but not desirable flying qualities. Prior to FBW aircraft, it was not possible to develop task-tailored flight control systems, and the pilots simply learned to live with less than optimum flying qualities for some tasks. One of the prime advantages of the new technology is the possibility for tailoring the flying qualities to the piloting tasks. An example of how the choice of the proper response-type can affect flying qualities was demonstrated in [BCS84]. During this investigation, a washout prefilter was added to some of the RCAH configurations converting them to ACAH configurations. Handling qualities ratings for the flared landing task improved dramatically from Level 2 and Level 3 to Level 1 just by changing response-types (see [Hoh88, p.18]).

Table 2.5. Qualities of Response-Types for the Precision Landing MTE [AGA91, p.22]

Qualities of Response-Types for the Precision Landing MTE		
Response-Type	**Advantages**	**Disadvantages**
Conventional	•Well accepted flare characteristics.	•Lightly damped phugoid mode. •Requires trimming to change airspeed during the approach. •AOA sensing required - gust sensitivity problems.
RCAH	•No trimming required to accomplish airspeed changes during the approach.	•Not as desirable for flare. •Not Level 1 if $1/T_q > 1/T_{\theta_2}$. •Tendency to float in flare. •Tendency for airspeed control problems during the approach (associated with division of attention).
ACAH	•Highly desirable flare characteristics.	•Requires trimming during approach.
GCGH	•Highly desirable flare characteristics.	•Requires trimming during approach. •May result in excessive speed bleedoff for unpowered approach in windshear. •Sensing requirements more complex than for ACAH.

2.5 Handling Qualities Metrics

Requirements for short-term (short-period) response have received a great deal of attention recently [MH90, p.20]. Since FBW aircraft are capable of unconventional responses and MIL-STD-1797A requirements were developed from flight test experience with conventional responses, many alternative criteria have been developed to predict flying qualities for modern aircraft. All have some degree of success in predicting handling qualities *if* properly applied. Ideally, it would be nice to have one stand alone criteria that predicts all. Unfortunately, no such criteria exists. In the past decade, the applicability of these competing criteria has become clearer and are outlined in [MH90, p.20-23].

Recommendations from Mitchell and Hoh for short term pitch response criteria are shown Table 2.6.

Table 2.6. Short Term Pitch Response Criteria [MH90, p.23]

Short Term Pitch Response Criteria			
Response-Type	Specification and Design Criteria	Criteria for Design Guidance Only	Criteria Not Applicable
Conventional	Bandwidth (or CAP) plus Dropback	$\omega_{sp}T_{\theta_2}$, Neal-Smith, Nichols chart Boundaries	TPR[5]
RCAH	Bandwidth plus Dropback	CAP, TPR, $\omega_{sp}T_{\theta_2}$, Neal-Smith, Nichols chart Boundaries	None
ACAH	Bandwidth	None	Dropback, CAP, TPR, $\omega_{sp}T_{\theta_2}$, Neal-Smith, Nichols chart Boundaries
GCGH	Bandwidth	None	Dropback, CAP, TPR, $\omega_{sp}T_{\theta_2}$, Neal-Smith, Nichols chart Boundaries

Since this study involves unconventional response-types, handling qualities metrics were selected *other* than the MIL-STD-1797A preferred forms (CAP or MIL-F-8785C criteria) developed for classical aircraft. This is consistent with the current literature (see [HM86, p.56-58] and [Hoh88, p.3-5]) and no attempt was made to use LOES matching.

Handling qualities specification for precision tracking with aircraft attitude is best accomplished with frequency based criteria [Hoh88, p.7]. These criteria emphasize features directly related to the piloted loop closure. Time domain criteria have been found to be more appropriate for use with lower frequency tasks such as pursuit tracking, gross flight path

[5]Transient peak ratio (TPR).

control, etc.. Most time domain criteria for attitude control are based on a step or boxcar input. Such inputs emphasize the mid and low frequency characteristics, at the expense of the response in the region of piloted crossover, which tends to be suppressed to the origin (the initial response). Other disadvantages of time domain criteria include the sensitivity of rise time to variations in the step input, atmospheric disturbances, and initial conditions as well as trying to estimate phase delay from the effective transport time delay which is also suppressed to the origin.

For the above reasons, the Bandwidth criterion was selected as the most applicable handling qualities metric for the response-types flight tested in this study. The Bandwidth criterion was supplemented with an STI modified Gibson Dropback criterion for the RCAH and conventional response-types for reasons to be discussed shortly. These two handling qualities metrics are discussed next.

2.5.1 Bandwidth Criterion The bandwidth criterion was developed as a generally applicable method to predict flying qualities for small amplitude, precision, closed-loop tracking tasks. It has been applied successfully to unconventional modes (such as wings level turns) and attitude control regardless of the response-type used. Most of the discussion below is from [Hoh88, p.5-6], [AGA91, p.30-32], [MAM90, p.35], and [HMH82]. Each reference contains background material or variations of the Bandwidth criterion not found in the others. The Bandwidth criterion has evolved since it was first developed and the variations of the Bandwidth criterion discussed here are either the latest versions published in the literature or were recommended by Mitchell (per phone conversations in 1992).

Classically, bandwidth is a term used to describe the ability of an electrical network or a servomechanism to follow a range of input frequencies. In that context, it is defined as the frequency where the output magnitude is 3 dB less than the input magnitude (0.707 ratio). A good system will have a high bandwidth, and a poor one will have a low bandwidth relative to the maximum input frequency it is designed to follow. In most cases, the upper bandwidth limit is set by system stability considerations.

The bandwidth frequency used as a flying qualities criterion is defined somewhat differently from the classical definition [Hoh88, p.5]. The Bandwidth criterion is an application of the crossover model developed by McRuer and Ashkenas. In this model, the pilot is treated as an element of a closed-loop system for compensatory tracking tasks. The Bandwidth criterion is based on the premise that the maximum crossover frequency a pure gain pilot can achieve, without threatening stability is a valid figure of merit of the controlled element (similar to a servomechanism).

Physically, the bandwidth is a measure of the frequency below which the pilot can follow commands, and above which he cannot. The characteristic frequency of the effective commands depends on the task, and so the bandwidth boundaries are *task dependent*.

Bandwidth is defined as the frequency where the phase margin is 45° or the gain margin is 6 dB. The phase margin criterion is based on pilot describing function data which shows that tracking with 45° of phase margin is representative of full attention, but less than maximum effort. A gain margin limit of 6 dB was selected based on experience which has shown that a lesser value tends to result in a PIO prone aircraft. Bandwidth is intended as an effective aircraft dynamic measure, relating the lead equalization required from the pilot to exert tight closed-loop control [MM88, Sup 3, p.6].

The Bandwidth criterion currently consists of two parameters, bandwidth (ω_{BW}) and phase delay (τ_p). Originally, the Bandwidth criterion consisted of just one parameter, ω_{BW}. However, efforts to develop the Bandwidth criterion as a generalized criterion for highly augmented aircraft, showed pilots were also sensitive to the shape of the phase curve at frequencies beyond the bandwidth frequency. This is defined by the phase delay parameter, τ_p. For large values of phase delay, the phase curve drops off more rapidly than for small values. Physically, phase delay is a measure of the behavior of the aircraft as the pilot increases his crossover frequency. Large values of phase delay mean there is a small margin (range of frequencies) between normal tracking at 45° of phase margin and instability. The inevitable pilot commentary for an aircraft with large phase delay is that it is PIO prone.

Phase delay, (τ_p), is typically (but not always) close to the equivalent time delay, (τ_e) calculated from LOES.

The Bandwidth criterion parameters are depicted in Figure 2.3.

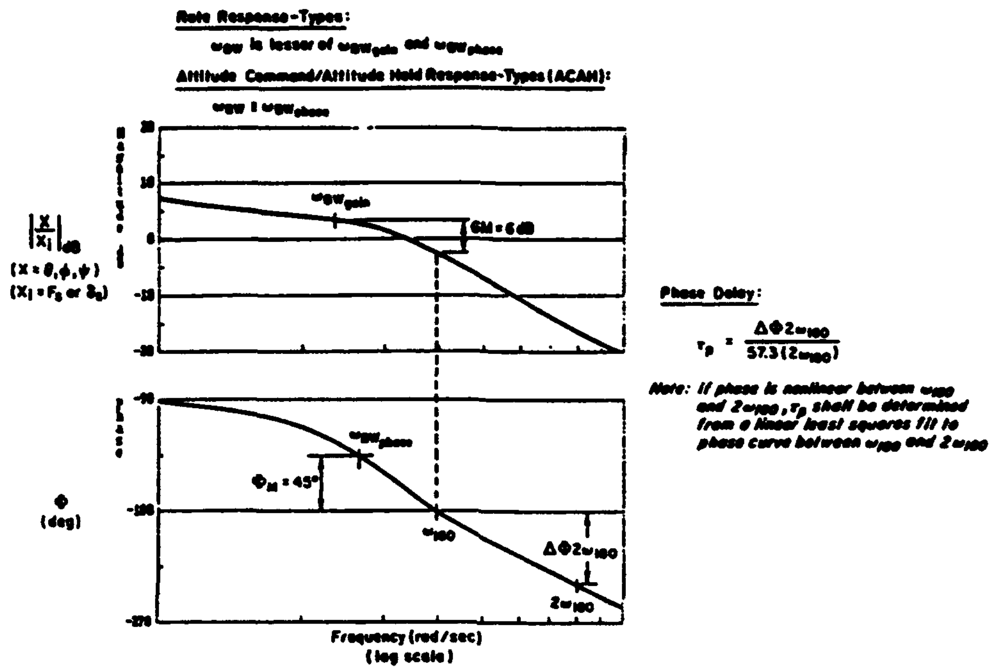

Figure 2.3. Bandwidth Criterion [MH90, p.25]

The pitch attitude bandwidth (ω_{BW_θ}) for rate response-types is the frequency at which the phase margin is 45° or the gain margin is 6 dB, whichever frequency is lower. In order to apply this definition, one first determines the frequency for neutral stability (ω_{180}) from the phase portion of the pitch attitude frequency response. The next step is to note the frequency at which the phase margin is 45°. This is the bandwidth frequency as defined by phase, $\omega_{BW_{phase}}$. Finally, note the amplitude corresponding to ω_{180} and add 6 dB. The frequency at which this value occurs on the amplitude curve is the bandwidth frequency as defined by gain, $\omega_{BW_{gain}}$. Pitch attitude bandwidth, ω_{BW_θ}, is the lesser of $\omega_{BW_{phase}}$ and $\omega_{BW_{gain}}$. If, $\omega_{BW_\theta} = \omega_{BW_{phase}}$, the aircraft is phase margin limited. If $\omega_{BW_\theta} = \omega_{BW_{gain}}$, the aircraft is gain margin limited; the aircraft is driven to neutral stability when the pilot

increases his gain by 6 dB (a factor of 2). Gain margin limited aircraft may have a great deal of phase margin, Φ_M, but increasing the gain slightly causes Φ_M to decrease rapidly. Such aircraft are characterized by frequency response amplitude plots which are flat (shelf like), combined with phase plots which roll off rapidly. Gain margin limited aircraft tend to be PIO prone. However, most aircraft are phase margin limited.

The pitch attitude bandwidth (ω_{BW_θ}) for attitude response-types is simply $\omega_{BW_\theta} = \omega_{BW_{phase}}$ [MAM, p.35].

The pitch attitude phase delay parameter (τ_{p_θ}) is calculated using

$$\tau_{p_\theta} = \frac{\Delta\Phi 2\omega_{180}}{\frac{180}{\pi}(2\omega_{180})} \quad \text{sec} \tag{2.14}$$

The term $\Delta\Phi 2\omega_{180}$ is the difference in phase between ω_{180} and $2\omega_{180}$. If the phase curve is nonlinear in this region, τ_{p_θ} is determined using a linear least squares fit.

For tasks where flight path control is also important, such as formation, air refueling, and landing, it is necessary to specify the bandwidth for both pitch attitude and flight path [AGA91, p.30]. If the γ/δ_{es} response does not involve significant equalization, the pilot is more likely to control γ directly (parallel) rather than through θ (series) [HM86, p.32]. The definition of flight path bandwidth (ω_{BW_γ}) differs slightly from pitch attitude bandwidth. Flight path bandwidth is defined only by the frequency for 45° of phase margin, $\omega_{BW_\gamma} = \omega_{BW_{phase}}$ [MAM, p.35]. In addition, there is no phase delay requirement.

The primary advantages of Bandwidth criterion are that it applies to all response-types, and hence is ideal for highly augmented aircraft, and is easily calculated from a frequency response of the higher order system (HOS). On the negative side, the calculation of bandwidth from flight test data requires a Fast Fourier transform on data which contains sufficient power at the frequencies of interest.

2.5.2 STI Dropback Criterion The Dropback and Nichols Chart Boundaries were developed by Gibson as design guidelines for highly augmented fighter aircraft. Dropback, as it is used in this study is a slightly revised definition from that proposed by Gibson (and adopted in MIL-STD-1797A). Most of the STI Dropback criterion material discussed below was taken directly from [MH90, p.22-43]. The STI Dropback criterion is shown in Figure 2.4.

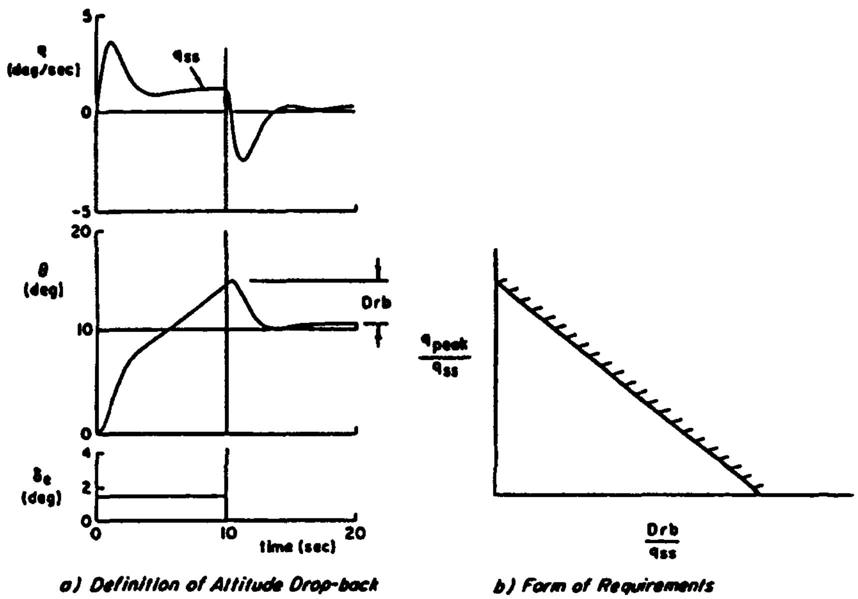

Figure 2.4. STI Dropback Criterion for Conventional and Rate Response-Types [MH90, p.24]

Dropback is applicable to conventional and rate response-types and is a measure of the mid-frequency response to attitude changes. Excessive dropback results in pilot complaints of abruptness and lack of precision in pitch control; complaints common also to aircraft with excessive values of pitch attitude bandwidth. This commonalty of piloting problems led to an analysis of handling qualities data to determine the applicability of the Dropback criterion.

High dropback cases occur for all values of bandwidth, though they are usually clustered at very high bandwidths (cases with low values of τ_{p_θ} and $\omega_{BW_\theta} = \omega_{BW_{phase}}$) and very low bandwidths (cases that typically have high $\omega_{BW_{phase}}$ but are gain-margin-limited due to excessive τ_{p_θ}). The Dropback criterion has successfully identified these aircraft (poor

handling qualities due to abruptness) that otherwise have acceptable bandwidths according to the Bandwidth criterion. In fact, dropback has been so successful at identifying poor aircraft that Mitchell and Hoh recommended removing the upper limits on bandwidth and replacing them with a limit on dropback [MH90, p.27]. However, dropback alone is not sufficiently discriminating, since HQRs below the dropback limit may be Level 1, 2, or 3. In other words, the Dropback criterion is *not* a stand-alone criterion for good handling qualities, some other criteria must also be applied. It does however, expose *bad* handling qualities.

The difference between Gibson's and STI's Dropback criterions is in the definition of the dropback parameter. Each has it's advantages and disadvantages. Gibson's dropback parameter, DB/q, is less susceptible to low-frequency responses than the STI dropback parameter, Drb/q. However, it is strongly influenced by time delay. Since dropback is a proposed limit on excessive mid-frequency abruptness, it is desirable to use a parameter that is not strongly affected by time delay, which is separately accounted for by τ_{p_θ}. However, the parameters used in the STI Dropback criterion are also time domain based, and are subject to many of the fundamental shortcomings of measurement such as what to do if the input is not a pure step, how to account for low frequency (phugoid) motions, how to define a steady-state pitch rate, etc..

All of the work to date on dropback has focused on aircraft that fit the definition of conventional or rate response-types; the Bandwidth criterion, however, has been successfully applied to all response-types. Removal of an upper limit on bandwidth therefore implies that a dropback-like criterion will be needed for attitude response-types. Since attitude response-types have a limited useful range of MTEs, and since the possibility of producing an attitude response-type is restricted to modern advanced control system schemes, there is very little experimental data for such systems. Therefore, it is difficult to

verify if an attitude equivalent to dropback is required, and impossible to define what such a criterion would look like[8].

The Bandwidth criterion currently does not identify this high dropback phenomena and as such requires another parameter to characterize mid-frequency abruptness. Just as the phase delay parameter was incorporated into the Bandwidth criterion to account for sensitivity to the shape of the phase curve, another parameter is required to account for sensitivity to abruptness. The Dropback criterion has successfully fulfilled this need for rate and conventional response-types. However, the current form does not work for attitude response-types and it's time domain nature is not ideally suited for use with flight test data.

2.5.3 Control Sensitivity It's possible to achieve both Level 3 and Level 1 flying qualities at the same value of bandwidth, simply by varying control sensitivity. A primary weakness of MIL-STD-1797A is the lack of adequate specification for control sensitivity. The following material is from [Hoh88, p.7-8] and [MH90, p.43-46].

Even the most experienced and perceptive test pilots can be and have been fooled by varying control sensitivity. Excessively high control sensitivity looks like low damping, is therefore PIO prone, and will receive comments to that effect (few if any, pilots will isolate the problem as excessively high control sensitivity). Similarly, excessively low control sensitivity will receive comments related to an overly sluggish response.

The control sensitivity should be specified over the band of frequencies where the pilot is most sensitive to the aircraft response. Since, by definition, the pilot is operating in the crossover region, the gain in this region should be specified. Recent work suggests the gain at the bandwidth frequency is a logical choice. Using this definition of control sensitivity, good correlation was obtained by crossplotting $|\theta/F_{es}|_{\omega_{BW_\theta}}$ vs. ω_{BW_θ} using data from two experiments (see [Hoh88, p.17]). This data indicates the proper control sensitivity depends

[8]A possible dropback criterion suggested by Mitchell and Hoh is a crossplot of $\theta_{peak}/\theta_{ss}$ vs. q_{peak}/θ_{ss} [MH90, p.39].

on bandwidth, with increasing bandwidth resulting in a requirement for decreasing control sensitivity and vice versa. Additionally, recent work has shown that aircraft with excessive control sensitivity *also* often exhibit excessive levels of dropback (see [MH90, p.46]. More data are required to set separate requirements for control sensitivity.

In the next chapter, all the ideas presented here (and more) were applied to the data from a previous handling qualities experiment in an effort to characterize acceptable (and unacceptable) conventional response-type dynamics for the probe and drogue air refueling task.

III. *An Analysis of a 1974 Calspan Experiment*

3.1 Introduction

In an effort to determine the important characteristics for the probe and drogue air refueling task, a previous handling qualities experiment was analyzed using modern handling qualities metrics. Both bandwidth and dropback trends for the configurations flown in a 1974 Calspan experiment [BCC74] were determined and plotted. These results were then compared with the pilot commentary with good correlation.

Since the probe and drogue air refueling task involves a high degree of precision pitch attitude *and* flight path control, both the pitch attitude and flight path bandwidths were evaluated. Control sensitivity was evaluated in terms $\left|\theta/F_{es}\right|_{\omega_{BW_\theta}}$, and a natural extension of this idea $\left|\gamma/F_{es}\right|_{\omega_{BW_\gamma}}$.

A great deal of emphasis is placed on pitch attitude control as if it's a means to an end. While it's true pilot's learn to use pitch attitude as a surrogate cue for flight path, ultimately pilot's are concerned with flight path when performing tasks in close proximity to another aircraft or the ground[1]. The need for good flight path control is essential. Data from both the Calspan and HAVE GAS experiments support that idea.

3.2 Calspan Experiment Design

In 1974 Calspan conducted a large two phase investigation of longitudinal flying qualities for fighters. The first phase of the investigation looked at the effect of evaluation technique and flight phase on flying qualities assessment. The probe and drogue air refueling task was chosen as one of the flight phases and handling qualities data in the form

[1]Pitch attitude is important during landing to avoid dragging the tail on the runway.

of pilot commentary and ratings were collected. Unfortunately, details of the task, desired and adequate task performance criteria, and actual success rates were not documented.

Although the second phase of the investigation involved criteria development, little analysis of the probe and drogue air refueling data was accomplished other than a discussion of the pilot commentary and *no* criteria development was attempted. The last conclusion from the first phase of the investigation was a recommendation to analyze the experiment in terms of the closed loop parameters developed in [NS70] (the Neal-Smith criterion) and the open loop parameters developed by Chalk, et al. for MIL-F-8785B. No published references were found indicating this analysis was accomplished.

The configurations evaluated in the probe and drogue air refueling task were a subset of the configurations used in the Neal-Smith handling qualities investigation. A total of fourteen conventional response-type configurations were evaluated by *one* pilot (Pilot A) during twenty-four blind evaluations[2]. Four basic short-period configurations were used to provide a baseline range of aircraft dynamics (configurations 1D, 2D, 4A, and 5A). Seven other configurations were developed by adding a first order lead or lag compensation in the command path (configurations 1B, 2A, 1E, 4D, 5D, 2J, and 5E). The added dynamics effectively shaped the pilot's stick force input and significantly altered the aircraft's short term response. Three additional configurations, with extreme combinations of ζ_{sp} and ω_{sp}, were also flown using stick position commands (configurations 9, 10, and 11)[3].

Table 3.1 lists the aircraft flight control system (AFCS) dynamics and pilot ratings for the probe and drogue air refueling task. The configurations are ranked ordered from best to worst based on the Cooper-Harper handling qualities ratings and PIO ratings assigned for each configuration. For convenience, the actuator dynamics are not included in Table 3.1.

[2]During a blind evaluation, the pilot is unaware of the configuration being evaluated.

[3]For these configurations the feel system is modeled in the command path.

Table 3.1. AFCS Dynamics and Pilot Ratings for Air Refueling Task [BCC74, p.44]

AFCS Dynamics and Pilot Ratings for Air Refueling Task				
Conf	$[\zeta_{sp}, \omega_{sp}]$	$\left(\frac{1}{\tau_1}\right)/\left(\frac{1}{\tau_2}\right)$	HQR	PIOR
1B	[0.7, 2.2]	(2)/(5)	1	1
2D	[0.72, 4.5]	—	1, 1, 2	1, 1, 1
2A	[0.72, 4.5]	(2)/(5)	2.5	1
11	[1.0, 3.3]	—	2.5	1
1D	[0.7, 2.2]	—	4.5, 4, 2	2, 1.5, 1
4A	[0.29, 4.5]	—	3, 4.5	1, 2
4D	[0.29, 4.5]	(∞)/(2)	4	2
5A	[0.18, 4.7]	—	4, 6, 5	2, 2, 2
10	[1.1, 2.3]	—	6, 4	3, 1.5
9	[1.7, 2.3]	—	5, 6, 5	2, 2, 2
5D	[0.18, 4.7]	(∞)/(2)	8	4
2J	[0.72, 4.5]	(∞)/(0.5)	8	4.5
5E	[0.18, 4.7]	(∞)/(0.5)	9	5
1E	[0.7, 2.2]	(∞)/(5)	10	5

As can be seen in Table 3.1, there is nearly a one for one relationship between the handling qualities ratings and the PIO ratings. The Level 1 configurations all had good short period dynamics or marginal short period dynamics augmented with lead dynamics. The Level 2 configurations all had marginal short period dynamics. The Level 3 configurations were primarily marginal short period dynamics further degraded by lag dynamics. It's clear the additional dynamics significantly altered the handling qualities. For instance, configuration 1D augmented with lead dynamics was the best configuration (configuration 1B, HQR = 1) and configuration 1D augmented with lag dynamics was the worst configuration (configuration 1E, HQR = 10). Handling qualities cannot be predicted from the short period dynamics alone.

3.3 *Analysis of Calspan Experiment*

The fourteen configurations were modeled in SIMULINK for analysis with the Bandwidth and STI Dropback criterions (and other selected control sensitivity parameters). Modeling the fourteen configurations required several calculations to convert the parameters published in [BCC74, p.44] into a transfer function gain (control gearing and elevator effectiveness) and to extend the published short period dynamics to include other responses of interest. The NT-33A data required to calculate elevator effectiveness are in Appendix B. The state-space realizations of transfer functions used to model the short period dynamics and flight control system dynamics are in Appendix C. Finally, the actual modeling of the fourteen configurations is documented in Appendix D.

MATLAB® M-files were written to automatically calculate all the parameters of both criterions. Because only short period dynamics were published (and modeled), the STI Dropback criterion was applied without incorporating the effects of the phugoid response.

3.3.1 Bandwidth Criterion Analysis Table 3.2 lists the Bandwidth criterion parameters for the Calspan configurations. Both $\omega_{BW_{phase}}$ and $\omega_{BW_{gain}}$ are listed for comparison with one another.

For the basic configurations, the magnitude of $\omega_{BW_{phase}}$ is close to, but larger than ω_{sp}. Addition of lead compensation in the command path increased both $\omega_{BW_{phase}}$ and $\omega_{BW_{gain}}$. Addition of lag compensation in the command path decreased both $\omega_{BW_{phase}}$ and $\omega_{BW_{gain}}$, and usually decreased $\omega_{BW_{gain}}$ substantially. Similar effects on $\omega_{BW_{\gamma}}$ are also observed. Lag compensation also increased phase delay to excessive levels.

These characteristics are shown graphically in Figure 3.1. The proposed Category A boundaries depicted in Figure 3.1 are from [MH90, p.48].

Table 3.2. Bandwidth Criterion Parameters for Calspan Configurations[4]

Bandwidth Criterion Parameters for Calpsan Configurations					
Conf	$\omega_{BW_{gain}}$ (rad/sec)	$\omega_{BW_{phase}}$ (rad/sec)	ω_{BW_θ} (rad/sec)	τ_{p_θ} (msec)	ω_{BW_γ} (rad/sec)
1B	9.67	4.44	4.44	18.6	1.56
2D	10.56	6.27	6.27	19.0	2.17
2A	12.87	8.36	8.36	19.1	3.28
11	5.23	3.86	3.86	56.6	1.18
1D	6.33	2.70	2.70	18.4	1.11
4A	7.07	5.13	5.13	19.9	3.23
4D	1.08	3.54	1.08	142.2*	1.29
5A	6.19	5.10	5.10	21.5	3.79
10	4.39	2.64	2.64	57.4	0.80
9	5.21	2.92	2.92	54.1	0.58
5D	0.61	4.01	0.61	139.0*	1.45
2J	2.29	1.02	1.02	121.3	0.38
5E	1.12	3.39	1.12	159.3*	0.46
1E	2.27	1.90	1.90	118.9	0.88

Except for configurations 4A and 5A, the data are generally in good agreement with the STI proposed bandwidth boundaries. These two configurations, as well as the high bandwidth configuration 2A, are flagged as high dropback cases and will be discussed subsequently in both the bandwidth and dropback analysis.

[4]Phase delays marked with an asterisk were determined using a least squares fit and are slightly lower than the values obtained using Eqn 2.14.

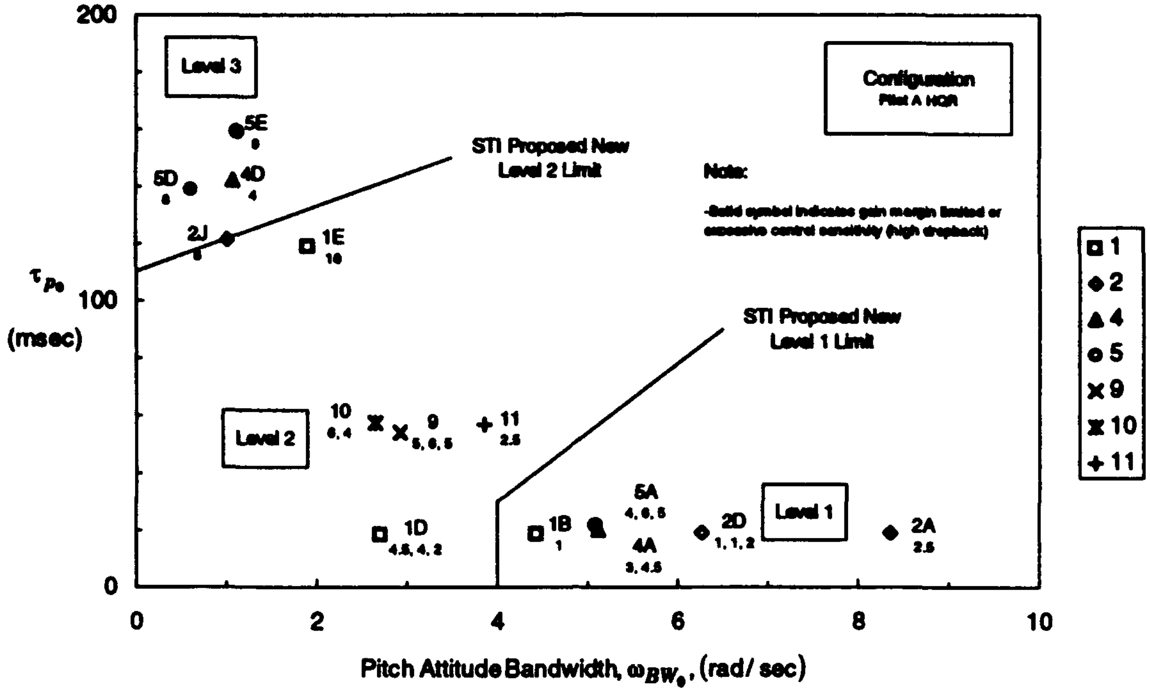

Figure 3.1. Bandwidth Criterion Analysis of Calspan Experiment

The three gain margin limited configurations (4D, 5D, and 5E) all have excessive phase lag and very low pitch attitude bandwidth. Pilot comments indicated configuration 4D could not be controlled precisely and there was a tendency to bobble the aircraft before getting to the drogue. Pilot comments indicated configurations 5D and 5E were extremely prone to PIO and totally unacceptable for the task. Both configurations exhibited poor pitch attitude control that deteriorated rapidly under tight control near the drogue. Two other configurations (2J and 1E) also had excessive phase lag and low pitch attitude bandwidth. Pilot comments for these configurations were similar to those of configurations 5D and 5E. Experience with these configurations indicate low pitch attitude bandwidth, excessive phase delay, and $\omega_{BW_\theta} = \omega_{BW_{gain}}$ equate to poor handling qualities.

Pilot comments for the medium bandwidth configurations (1D, 9, 10, and 11) indicated slow initial responses and a fair to poor ability to trim. Several hookups involved one to two oscillations near the drogue. The prevailing comment was an inability to make a fine correction near the drogue which gave a feeling of lack of precise control. Performance was

dependent on the level of pilot aggressiveness. Attempts to exert tight control near the drogue resulted in undesirable motions (PIO tendencies).

Configuration 11 plotted in the Level 2 region of Figure 3.2. This configuration was evaluated only once in the probe and drogue air refueling task and was rated Level 1. Pilot comments for configuration 11 were similar to those for configurations 1D, 9, and 10 except for comments on how aggressiveness affected the handling qualities (for which there were no comments). Pilot comments for configuration 11 in HUD tracking tasks by the same pilot indicated the slow initial response was more objectionable for these tasks and the aircraft was rated Level 2.

Pilot comments for the higher bandwidth Level 1 configurations (1B and 2D) were favorable. The key comments were an ability "to think the airplane right into position" and the ability to make a fine correction near the drogue at will. The initial response for configuration 2D was a little rapid resulting in a tendency to bobble the aircraft slightly on some hookups, but was considered a minor objection.

Other comments made by Pilot A were also significant for determining desirable vehicle dynamics. Configurations 1B and 2D gave Pilot A a feeling of precision that allowed him to look directly at the drogue throughout the approach and center the probe in the drogue. Attempts to do this with many of the other configurations resulted in overcontrol near the drogue and so the tanker became the primary reference during evaluations of poor handling configurations.

Flight path bandwidth analysis is accomplished by crossplotting Calspan experiment flight path bandwidths against pitch attitude bandwidths. Results are shown in Figure 3.2.

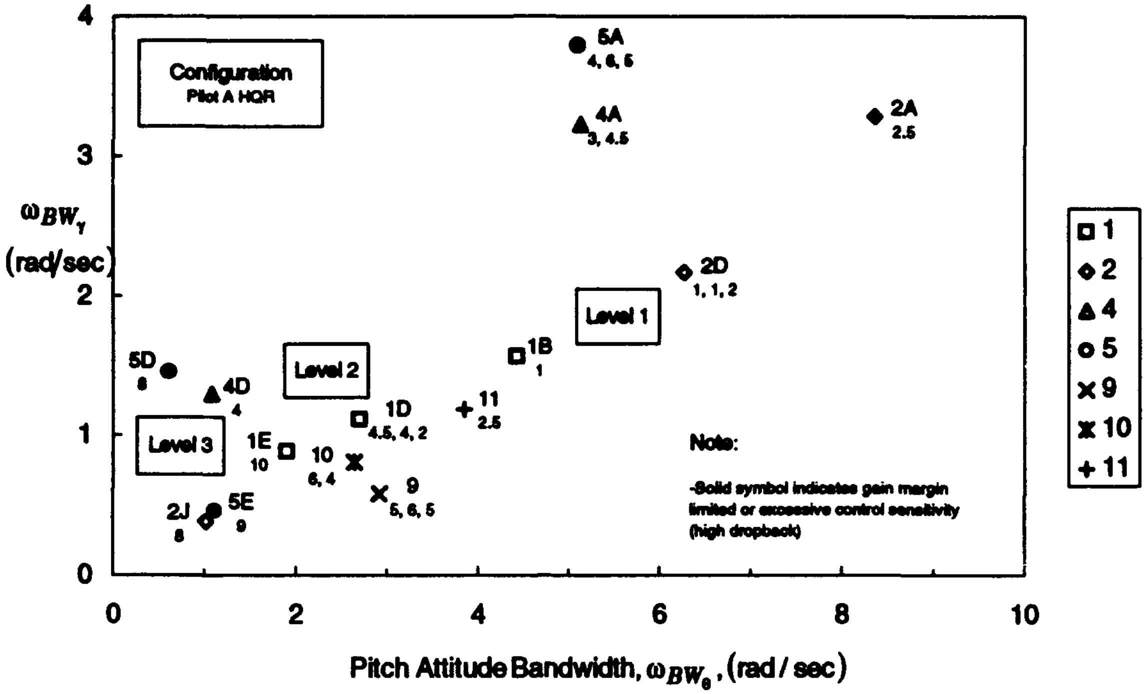

Figure 3.2. Pitch Attitude and Flight Path Bandwidths for Calspan Experiment

Regions of Level 1, 2, and 3 handling qualities can be identified based on bandwidths. Excluding the high dropback configurations (2A, 4A, and 5A), the general bandwidth trend is clear. Level 3 aircraft have low values of pitch attitude and flight path bandwidths, Level 2 aircraft have medium values of pitch attitude bandwidth and low values of flight path bandwidth, and Level 1 aircraft have higher pitch attitude and flight path bandwidths, possibly in the right combination.

The three high dropback configurations all had high values of flight path bandwidth. At first it would appear that high flight path bandwidth is to be avoided. However, closer inspection reveals why both ω_{BW_θ} and ω_{BW_γ} are high for these configurations and also why the Bandwidth criterion fails to identify the poor handling qualities.

Both configurations 4A and 5A had low values of short period damping ($\zeta_{sp} = 0.29$ and $\zeta_{sp} = 0.18$, respectively) and received pilot comments of oscillatory initial and final responses. In terms of frequency response, the phase contribution of a lightly damped second order system (i.e. short period) is little phase lag until near $\omega/\omega_{sp} = 1$ followed by

considerable phase lag (a rapid change of $-180°$ in the vicinity of $\omega/\omega_{sp}=1$). Likewise, the magnitude of the θ/F_{es} and γ/F_{es} remains high in the region around $\omega/\omega_{sp}=1$ (in the region of piloted crossover). This behavior happens slightly before $\angle\theta/F_{es}=-180°$ and at $\angle\gamma/F_{es}=-180°$ for configurations 4A and 5A as can be seen in Figures 3.3 and 3.4.

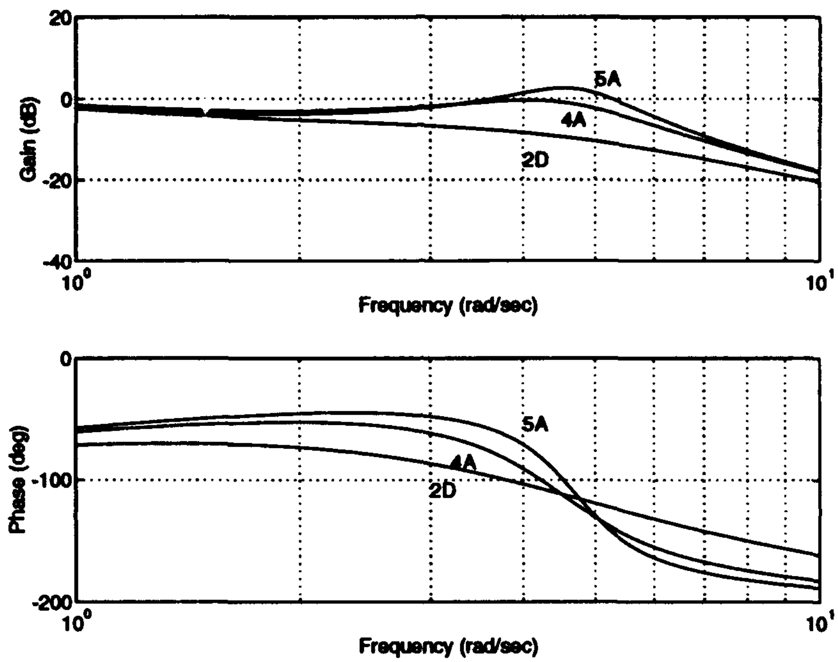

Figure 3.3. θ/F_{es} Frequency Response Comparison for Selected Calspan Configurations

For these lightly damped configurations, $\angle\theta/F_{es}=-135°$ occurs at a frequency only slightly less than the well damped configuration 2D (5.1 rad/sec for both configurations 4A and 5A versus 6.3 rad/sec for configuration 2D). Certainly nothing that stands out as $\omega_{BW_{phase}}$ is still large. The frequency where $\angle\theta/F_{es}=-180°$ for configurations 4A and 5A is much less than that for configuration 2D. But, because the slope of $|\theta/F_{es}|$ is changing at a rate of approximately 40 dB/decade in this region, $\omega_{BW_{gain}}$ occurs only slightly below ω_{180} and *still* above $\omega_{BW_{phase}}$. According to the Bandwidth criterion, both aircraft are phase margin limited with good bandwidth. Also, because the phase doesn't roll off quickly after

crossing −180°, the phase delay is low. The Bandwidth criterion parameters all indicate a good aircraft and the pilot comments and ratings all correctly indicate a bad aircraft.

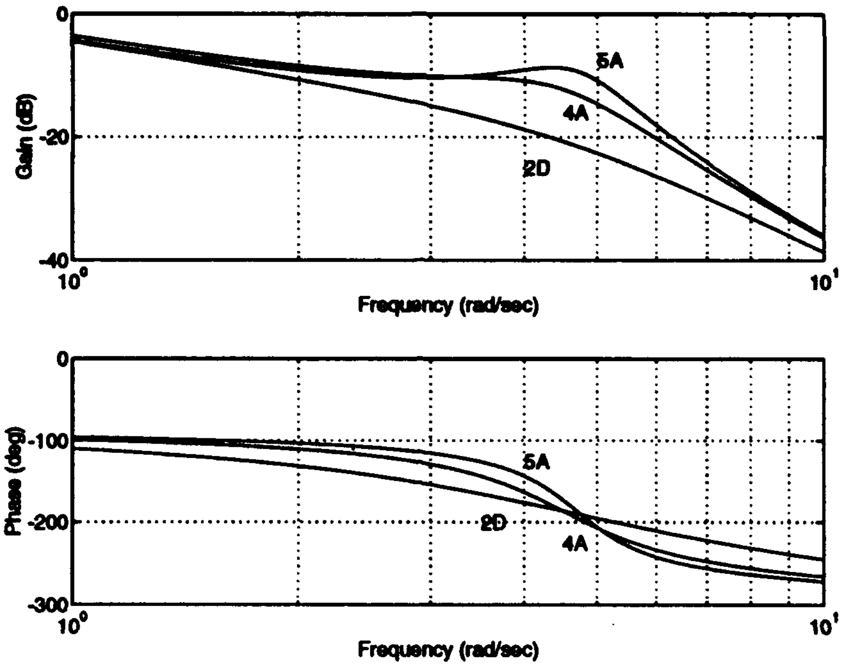

Figure 3.4. γ/F_{es} Frequency Response Comparison for Selected Calspan Configurations

The conventional response-type flight path bandwidth is affected somewhat differently by low short period damping ratio. Instead of a reduction in bandwidth, there's a sizable increase. Again, the lightly damped short period contributes little phase lag until near $\omega/\omega_{sp} = 1$. As ζ_{sp} decreases, the frequency where $\angle\gamma/F_{es} = -135°$ (i.e. ω_{BW_γ}) increases.

These trends are easily quantified using the short period approximations for a conventional aircraft. The influence of ω_{sp}, ζ_{sp} and $1/T_{\theta_2}$ on ω_{BW_θ} and ω_{BW_γ} for a phase margin limited conventional response-type (with no added flight control system dynamics) can be determined to a first order approximation by a truncated Taylor series expansion of the equations $\angle\theta/F_{es} = \angle\gamma/F_{es} = -135°$. The results are

$$\omega_{BW_\theta} \cong \omega_{sp}\left[\frac{\pi\zeta_{sp}}{4}+\sqrt{\frac{\pi^2\zeta_{sp}^2}{16}-\frac{2\zeta_{sp}}{\omega_{sp}}\frac{1}{T_{\theta_2}}+1}\right] \tag{3.1}$$

$$\omega_{BW_\gamma} \cong \omega_{sp}\left[-\frac{4\zeta_{sp}}{\pi}+\sqrt{\frac{16\zeta_{sp}^2}{\pi^2}+1}\right] \tag{3.2}$$

As ζ_{sp} goes to 0, both ω_{BW_θ} and ω_{BW_γ} go to ω_{sp}. For a fixed value of ζ_{sp}, ω_{BW_γ} varies linearly with ω_{sp}. For a conventional response-type, high flight path bandwidth according to the Bandwidth criterion *equates* to low damping and large ω_{sp}. This result is unique for a conventional response-type in that RCAH and ACAH response-types (superaugmented) require larger ζ' to satisfy MIL-F87242 flight control system stability margins. As will be shown in the next chapter, ACAH response-types can achieve high flight path bandwidths according to the Bandwidth criterion with larger ζ'.

Clearly, the Bandwidth criterion predictions of a pilot's ability to control pitch attitude and flight path (i.e. high ω_{BW_θ} and ω_{BW_γ}) with a lightly damped aircraft are incorrect. The pilot doesn't really have good control of pitch attitude and better control of flight path, he has worse, much worse. The physical interpretation of bandwidth as a measure of the frequency below which a pilot can follow commands and above which he cannot, breaks down.

Configuration 2A had good short period dynamics $[\zeta_{sp}, \omega_{sp}]$ but incorporated lead compensation. This configuration was only evaluated once in the probe and drogue air refueling task and was given a Level 1 HQR. However, pilot comments indicated the aircraft was sensitive. Evaluations with configuration 2A in other tasks indicated the initial response was fast, approaching abrupt. The qualitative effect of lead compensation in the region of piloted crossover is the addition of gain and phase. In some cases, this is beneficial (lead compensation added to configuration 1D resulted in the best 1974 configuration). In other cases, it's not (lead compensation added to configuration 2D resulted in degraded

handling qualities due to abruptness of the initial response). The important point is the Bandwidth criterion predicts any addition of phase in the region of piloted crossover is beneficial (i.e. higher ω_{BW_θ} and ω_{BW_γ}). Clearly, this is not always true.

In these cases, the Bandwidth criterion fails to identify that the true behavior of θ/F_{es} and γ/F_{es} (important responses to the pilot) deviate substantially from the desired $\cong K/s$ like behavior in the region of piloted crossover. That $\cong K/s$ like behavior for θ/F_{es} and γ/F_{es} in the region of piloted crossover is important, can been seen in the frequency responses for configuration 2D (shown in Figures 3.3 and 3.4).

Considerable information is lost when the characteristics of an entire frequency response are boiled down to one or two numbers. This analysis exposes the reasons the Bandwidth criterion required supplementing with the STI Dropback criterion. Frequency response information lost in the region of piloted crossover was regained by another metric. However, the information is still in the frequency response. Modifying the Bandwidth criterion to include this information is beyond the scope of this effort and probably unnecessary. A Level 2 or 3 high bandwidth, phase margin limited conventional response-type aircraft that plots in the Level 1 region of Figure 3.1 (and the higher flight path bandwidth area of Figure 3.2) will have excess $|\theta/F_{es}|$ and $|\gamma/F_{es}|$ compared to a Level 1 aircraft with the same pitch attitude bandwidth. Crossplotting $|\theta/F_{es}|_{\omega_{BW_\theta}}$ vs. ω_{BW_θ} and/or $|\gamma/F_{es}|_{\omega_{BW_\gamma}}$ vs. ω_{BW_γ} should expose the problem. This can be viewed as a control sensitivity issue since the overriding pilot comments for these aircraft are related to the aircraft being too responsive and PIO prone. This will be discussed further in the control sensitivity analysis section.

These cases should be viewed as exceptions since they represent aircraft that are not practical. Historically, the problems encountered with highly augmented aircraft have more to do with excessive phase lag and the phase delay parameter very much characterizes the behavior of $\angle\theta/F_{es}$ beyond $-180°$ where high frequency lags contribute to rapid phase roll off. The Bandwidth criterion has worked successfully with highly augmented aircraft.

3.3.2 Control Sensitivity Analysis Table 3.3 lists control sensitivity parameters for the Calspan configurations.

Table 3.3. Control Sensitivity Parameters for Calspan Configurations

Control Sensitivity Parameters for Calspan Configurations						
Config	q_{pk}/q_{ss} (—)	Drb/q_{ss} (sec)	F_{es}/n (lb/ g)	$\dot{q}/F_{es}$ $(\mathrm{deg/lb \cdot sec^2})$	$\lvert\theta/F_{es}\rvert_{\omega_{BW_\theta}}$ (dB)	$\lvert\gamma/F_{es}\rvert_{\omega_{BW_\gamma}}$ (dB)
1B	1.65	0.53	5.8	4.53	−12.32	−6.64
2D	2.02	0.51	6.5	6.33	−13.20	−11.51
2A	3.34	0.77	5.6	14.12	−9.39	−10.62
11	1.32	0.27	12.0	1.65	−18.94	−12.34
1D	1.33	0.32	5.8	2.27	−9.69	−4.65
4A	3.14	0.70	6.1	8.91	−2.86	−10.24
4D	1.81	0.36	11.1	1.51	−8.08	−12.30
5A	3.73	0.75	6.7	9.41	0.89	−9.49
10	1.04	0.04	6.2	1.65	−13.34	−3.54
9	1.00	0.00	8.2	1.13	−3.79	−3.79
5D	2.04	0.40	8.9	2.25	−2.30	−11.51
2J	1.00	0.00	5.4	0.66	−7.96	3.44
5E	1.00	0.00	7.6	0.84	−11.60	−1.59
1E	1.29	0.29	8.7	0.92	−9.85	−6.16

For the Calspan experiment, the desired F_{es}/n was in the range 4.5 to 7.0 lb/g, however, the evaluation pilot was allowed to reselect gearing if he felt the gearing was unsatisfactory and a degrading factor on the handling qualities of the configuration or the conduct of the evaluation. The best aircraft for the task had an $F_{es}/n \approx 6\ \mathrm{lb}/g$.

The pitch acceleration per lb of stick force input varied considerably among the aircraft. Even among the Level 1 aircraft there was no real trend. The two best configurations had a $\dot{q}/\mathrm{lb} \approx 5.4\ \mathrm{deg/lb \cdot sec^2}$.

The dropback tendencies for the Calspan configurations are depicted graphically in Figure 3.5. The proposed excessive dropback boundary is from [MH90, p.28].

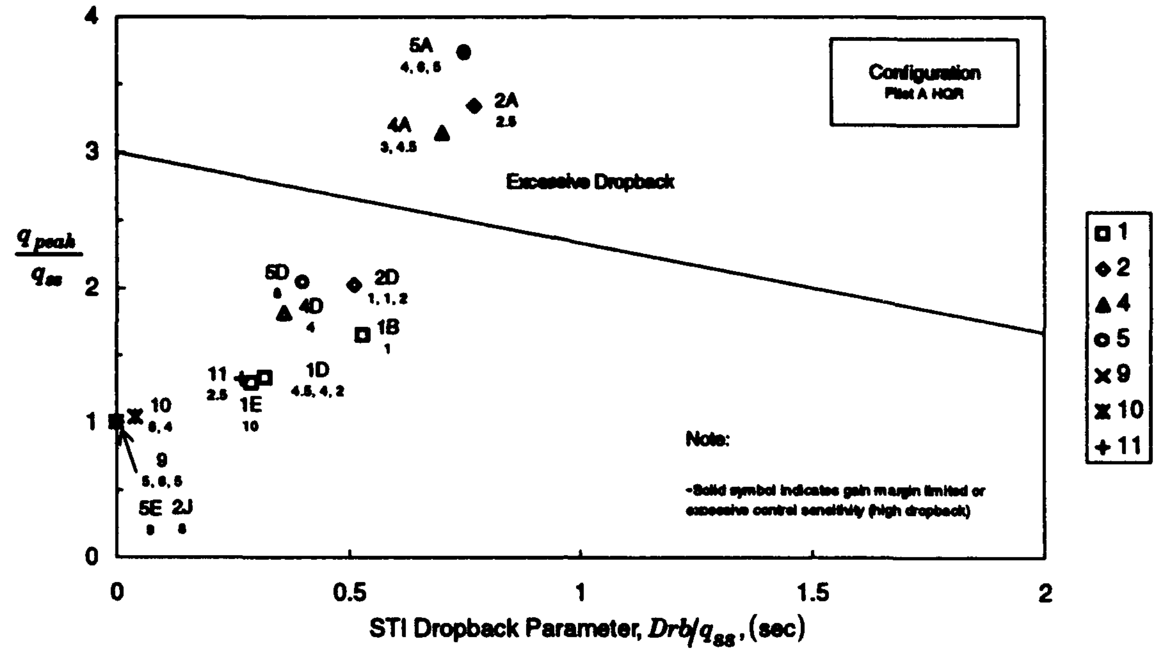

Figure 3.5. Dropback Tendencies for Calspan Experiment

Three configurations are identified as high dropback cases. Configurations 4A and 5A both have marginal short period dynamic[illegible] $=0.29$ and $\zeta_{sp}=0.18$, respectively. These configurations primarily received Level [illegible]dling qualities ratings. Configuration 2A represented good short period dynamics augmented with lead compensation. This configuration was evaluated only once in probe and drogue air refueling and received a Level 1 HQR. However, pilot comments indicated the stick forces were light and the aircraft was a little sensitive. Pilot comments from evaluations of configuration 2A in other tasks, such as air combat maneuvering (ACM), indicated a persistent bobbling tendency and a fast initial response approaching abrupt. It's possible the level of aggressiveness used in the one air refueling evaluation did not expose the abruptness problems with configuration 2A.

The control sensitivity problems for configurations 2A, 4A, and 5A can also be identified by crossplotting $|\theta/F_{es}|_{\omega_{BW_\theta}}$ vs. ω_{BW_θ} (Figure 3.6) and $|\gamma/F_{es}|_{\omega_{BW_\gamma}}$ vs. ω_{BW_γ} (Figure 3.7). The control sensitivity boundary in Figure 3.6 was determined using the depicted high dropback Neal-Smith cases in [MH90, p.46].

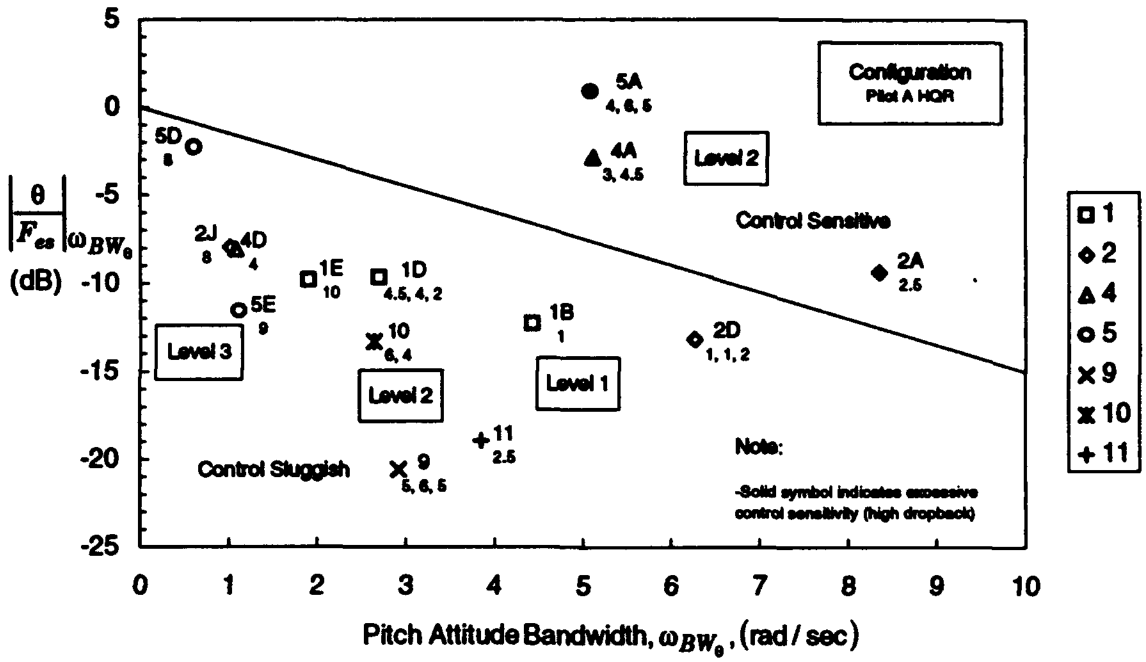

Figure 3.6. θ/F_{es} Control Sensitivity Analysis of Calspan Experiment

In Figure 3.6 the three oversensitive aircraft plot in the upper right region indicating $|\theta/F_{es}|$ was excessive in the region of piloted crossover. The Level 1 aircraft lie in the middle. Pilot comments indicated stick forces were slightly light for configuration 2D and it does, in fact, lie to the right of configuration 1B. The more sluggish configuration 11 lies to the left and low from configuration of 1B. Level 2 aircraft are just to the left of the Level 1 aircraft and further to the left are the Level 3 aircraft. The data clearly show that $|\theta/F_{es}|$ must decrease as ω_{BW_θ} increases for acceptable control sensitivity.

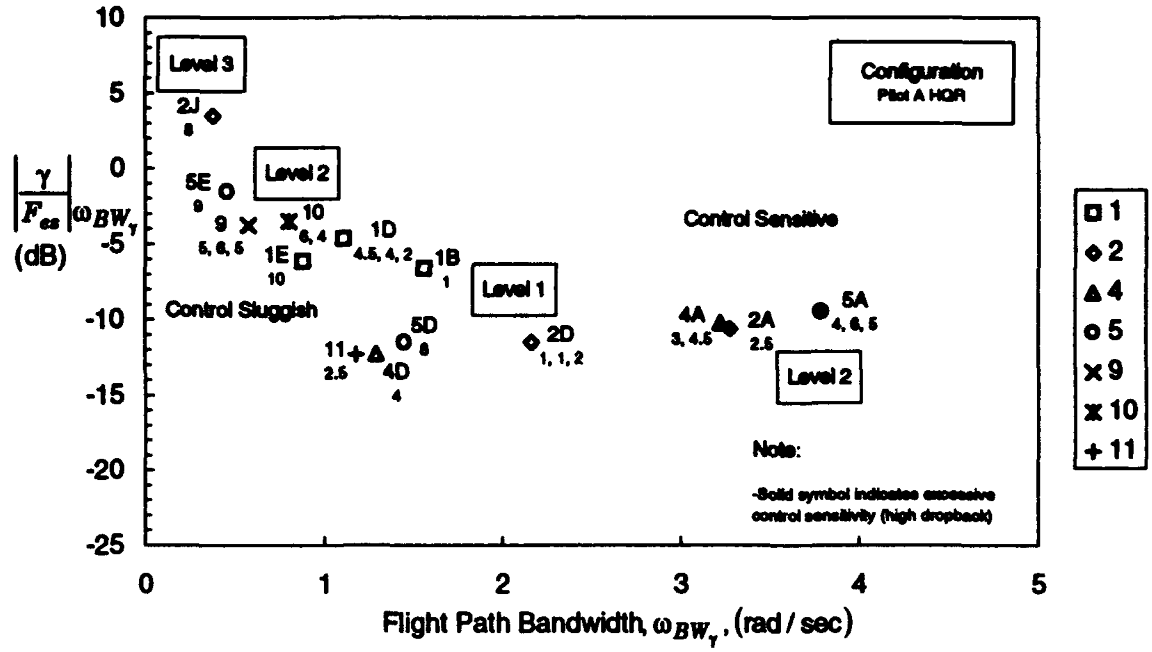

Figure 3.7. γ/F_{es} Control Sensitivity Analysis of Calspan Experiment

Figure 3.7 shows a similar trend, however, both Level 2 and Level 3 aircraft are mixed together to the left of the Level 1 aircraft. The three overly sensitive aircraft are all well right of the others.

These trends will be further reinforced with data from the HAVE GAS experiment. Another advantage of crossplotting $|\theta/F_{es}|_{\omega_{BW_\theta}}$ vs. ω_{BW_θ} and $|\gamma/F_{es}|_{\omega_{BW_\gamma}}$ vs. ω_{BW_γ} is the exposure of control sensitivity problems due to excessive command gains. This will also become apparent later (Chapter 6).

IV. Flight Control System Design

4.1 Introduction

A major topic of the literature review not yet discussed is flight control system design. In particular, how to make an aircraft fly differently from a conventional aircraft. Several handling qualities experiments were reviewed to determine the methods used in previous handling qualities experiments. At least two different approaches to flight control system design surfaced. One involved model following and the other superaugmentation.

There are two forms of model following: implicit model following and explicit model following. The appeal of model following control synthesis techniques is the ability to incorporate handling qualities specifications directly into the design process (see [AS91], [AS87], [AS86], and [Ryn85]). However, there are also several problems with model following when trying to achieve a *practical* unconventional response-type (not the least of which is handling qualities specifications don't yet exist for unconventional response-types). Implicit model following is sensitive or non-robust, requiring precise knowledge of the stability and control derivatives of the vehicle. Feedforward and feedback gains must be gain scheduled as a function of flight condition. Explicit model following is more robust but also requires a more complex control law involving a dynamic model. An attempt to achieve pitch rate command response-types using explicit model following in the TIFS lead to some controversial results (flight test report documented in [WBRS86] and briefly analyzed in [HM86, p.58-64]). Based on these flight test results and problems encountered with Rynaski's flight control system design techniques using robust output observers[1] lead to rejection of the model following approach.

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[1]Results published in [Ryn82] could not be duplicated when actuator effects were included.

Superaugmentation represents a practical way to achieve an unconventional response-type. Superaugmented aircraft are statically unstable without augmentation and have a degree of pitch attitude stability with respect to inertial space (as opposed to a conventional weathervane stability) which is provided by the flight control system. Also, the pitch response characteristics are largely independent of the aerodynamic stability derivatives (except for pitch control effectiveness and static stability) [MJM86, p.530]. The predominant dynamic effect of static instability is an unaugmented aircraft alone divergence that requires a high gain, large bandwidth controller for stabilization. Such systems reduce the system sensitivity to many aircraft characteristics. In solving the control problem, an equivalent vehicle is created in which some of the dynamic properties presented to the pilot depend primarily on the control dynamics. Hence, there is a great potential for tailoring some of the effective aircraft dynamics by appropriate controller adjustments and forms.

Past handling qualities investigations conducted by Calspan have looked at the suitability of superaugmented aircraft for the flared landing task. Results from these experiments showed RCAH response-types exhibit mediocre to poor flying qualities for landing. Pilots reported poor control of the flight path and tendencies to balloon and float during landings [Cha86, p.541]. Results from the flight test report [BCS84, p.4-12] also indicated dramatic improvement in flying qualities by switching from a RCAH to an ACAH response-type through the addition of a washout prefilter. While much experience has been gained with unconventional response-types in the flared landing task, little dedicated handling qualities research has been accomplished for other tasks.

The superaugmented flight control system architecture chosen for this experiment was essentially that proposed by Myers, McRuer, and Johnston in [MMJ84] and was similar to that used during the flared landing task experiments conducted by Calspan[2]. This was done

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[2]That experiment used the TIFS instead of the NT-33A and incorporated turn compensation in the design.

deliberately to keep the flight control system architecture as simple as possible (yet still representative of current aircraft) and to minimize technical risk. It also allowed the evaluation of a wide range of dynamics from pure RCAH, to pseudo conventional (RCAH extended bandwidth), to ACAH. The inclusion of two conventional response-types from the previous probe and drogue experiment allowed a direct comparison of three different response-types.

The flight control system design begins with a recognition of the limitations of the NT-33A simulation. Next, the short period dynamics of the NT-33A are altered to achieve a simulated RSS fighter type bare airframe. A superaugmented flight control system using pitch rate feedback is wrapped around this airframe and the basic flight control system stability margins determined as functions of the key flight control system parameters (loop gain and zero location of the proportional plus integral controller). Finally, the handling qualities implications of three different prefilters are examined in terms of the Bandwidth and Dropback criterions.

Unfortunately, neither an accurate model for the NT-33A nor the details of the NT-33A digital flight control system filtering were made available during this early work. An accurate model for the NT-33A was not really necessary at the time since the NT-33A was destabilized immediately in the VSS feedback loops (new VSS gains were calculated once a better model was obtained). Actuator dynamics and computational delays (modeled with a Páde approximation) were incorporated in the flight control system right from the start. Flight control system stability margins remained approximately the same between the initial and final designs (computational delay was increased from 20 to 25 msec and two very high frequency filters were added in the final designs). However, the addition of anti-aliasing filters to the command path increased the phase lag noticeably (and reduced the bandwidth for the pilot loop). The handling qualities predictions from this early work are optimistic and represent the upper limits of achievable performance. However, they demonstrate the basic trends very well.

4.2 NT-33A Simulation Method

By using response feedback, the NT-33A's analog variable stability system (VSS) alters the NT-33A airframe dynamics to simulate the unaugmented dynamics of other aircraft. A programmable digital flight control system is then wrapped around this bare airframe to evaluate a candidate flight control system. A variable feel system allows inflight adjusting of this important part of the flight control system as well. Figure 4.1 shows the basics of the NT-33A simulation method.

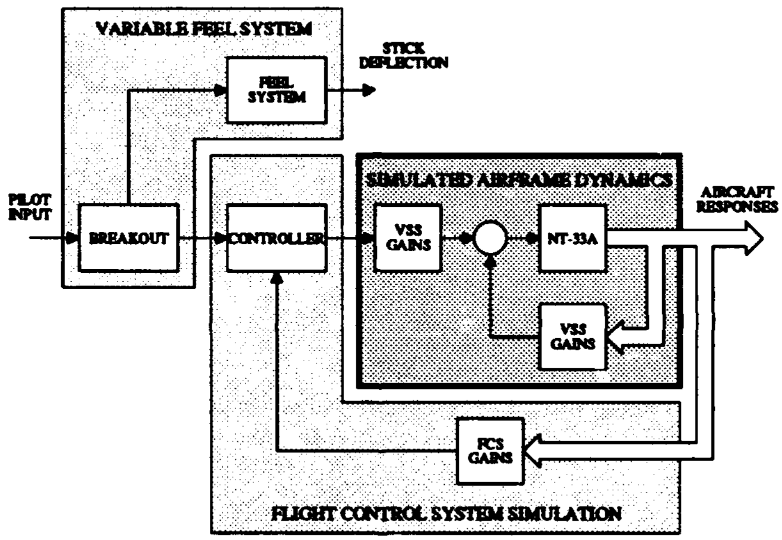

Figure 4.1. NT-33A Simulation Method

There are some important limitations to the simulation. Since the NT-33A has one longitudinal controller, a conventional elevator, only the moment stability derivatives, M_u, M_α, $M_{\dot{\alpha}}$, M_q, and M_{δ_e} can be altered. In other words, the NT-33A VSS using only elevator control has 5 parameters available with which to simulate the longitudinal motions of an aircraft described by 15 parameters [HH70, p. 108]. This is not as serious a drawback as it might first appear since usually $X_{\dot{\alpha}}$, X_q, $Z_{\dot{\alpha}}$, Z_q, and X_{δ_e} are approximately zero (the first four were assumed to be zero in arriving at Eqn 2.1). However, one important stability derivative, Z_w, can't be altered (significantly) with just the elevator. This stability

derivative is the *dominate* parameter in the pitch attitude transfer function zero, $1/T_{\theta_2}$, and is directly related to the lift curve slope of the aircraft (C_{L_α}). To a first order approximation, $1/T_{\theta_2}$ characterizes the lag between a pitch attitude change and the resulting flight path change. The stability derivative Z_w also appears in the characteristic equation and influences the location of the bare airframe short period pole locations.

Controlling Z_w directly requires the ability to vary lift directly (such as direct lift flaps). This is a capability the NT-33A does *not* have. Without this capability, the value for Z_w is *always* the NT-33A's value.

The nondimensional stability derivatives that influence Z_w are C_{L_α} and C_D, with C_{L_α} dominant

$$Z_w = \frac{\rho S U}{2m}(-C_{L_\alpha} - C_D) \qquad \frac{1}{\text{sec}} \tag{4.1}$$

Unfortunately, the NT-33A is a medium performance jet and does not have a lift curve slope representative of most modern high performance fighters. The NT-33A has a classic subsonic wing (no sweep, mild taper, relatively high aspect ratio, and a thick airfoil). Most modern fighters sport a thin, swept, highly tapered, low aspect ratio wing. As Gibson points out, the NT-33A's small value of T_{θ_2} ($1/T_{\theta_2} \cong -Z_w$) is not *fully* representative of modern higher wing loading configurations at refueling altitudes, where for similar path delays the attitude transients are larger [Gib91, p.9-5]. Using the data from [Hef72, p.23], Z_w for the NT-33A at 20,000 ft pressure altitude (PA) and 252 KIAS is[3,4]

$$Z_w = -1.2488 \qquad \frac{1}{\text{sec}} \tag{4.2}$$

The nondimensional terms of Z_w for the NT-33A are compared with the nondimensional terms of Z_w for several fighters in Table 4.1. The F-16 data were from

[3]Appendix B lists the stability derivatives for both stability and body axes.

[4]Data from [Kno86a] indicate $Z_w = -1.1939\ \text{sec}^{-1}$ at 10,000 ft PA.

[HMA81, p.114], the F-15 data were from [Bla91, p.603], and the A-4D data were from [MAG73, p.701] and [Nel89, p.254]. The data from these references apply to similar flight conditions (the nondimensional terms were assumed to remain constant if slight differences did exist).

Table 4.1. Comparison of Selected Nondimensional Stability Derivatives

Comparison of Selected Nondimensional Stability Derivatives			
Aircraft	$-C_{L_\alpha} - C_D$ (1/rad)	C_{M_q} (1/rad)	$C_{M_{\dot{\alpha}}}$ (1/rad)
NT-33A	-5.28	-10.80	-3.40
F-16A	-4.14	-4.46	-1.55
F-15A	-4.22	-4.00	0.00
A-4D	-3.48	-3.85	-1.27

The NT-33A value for Z_w is on the average over thirty percent higher than the other jet fighters listed in Table 4.1. When simulating other aircraft, the NT-33A can sometimes match the other aircraft's Z_w by appropriate choice of flight condition. The n_z/α, q, and α responses can then be adequately simulated. However, the probe and drogue air refueling task is usually performed near 250 KIAS and at medium altitudes and so does not allow great flexibility in changing flight conditions. Rather than attempt to simulate any specific fighter by some complicated choice of flight condition and matching scheme, the limitation to the simulation was recognized. The higher than desired influence of Z_w on the aperiodic short period poles of a simulated RSS bare airframe was offset by appropriate choice of α and q feedbacks as described in the next section. The higher NT-33A value of Z_w, however, still influences the aircraft responses according to the approximations listed in Table 2.4 (note the $\left(1/T_{\theta_2}\right)$ dynamics in denominators of the RCAH and ACAH α and γ responses).

4.3 *Simulated RSS Fighter Airframe Dynamics*

Simulation of a RSS fighter begins with knowledge of the NT-33A dynamics. A four state model was constructed from stability derivatives for the NT-33A. The key stability derivative changes required to destabilize the NT-33A were determined by looking at the short period approximation of the NT-33A. These stability derivatives can't be specified directly because the NT-33A uses response feedback to effectively alter moment stability derivatives. To a first order approximation the gains required to achieve the desired new stability derivatives are calculated algebraically assuming perfect actuation. Next the effects of actuation are included in the simulation and the feedback gains adjusted to get back to the desired short period pole locations.

4.3.1 NT-33A Linear Model The NT-33A aerodynamic data from [Hef72, p.5-31] were used during the initial design studies and are listed in Appendix B. The flight condition selected was 20,000 ft PA and 0.55 Mach (252 KCAS). Although certainly not necessary, stability axes were selected for modeling and the body axis stability derivatives from [Hef72, p.23] were transformed using the equations in Appendix A. These stability derivatives were then substituted in Eqn 2.7 and a similarity transformation performed so angles are in degrees and angular rates in deg/sec instead of radians and rad/sec respectively.

The resulting state space representation of the NT-33A is

$$A_{NT-33A} = \begin{bmatrix} -1.2488e+00 & 0 & 1 & -1.2498e-02 \\ 0 & 0 & 1 & 0 \\ -8.5615e+00 & 0 & -1.2894e+00 & -1.9189e-02 \\ 2.1652e-01 & -5.6200e-01 & 0 & -8.5402e-03 \end{bmatrix} \tag{4.3}$$

$$B_{NT-33A} = \begin{bmatrix} -7.1760e-02 \\ 0 \\ -1.4178e+01 \\ -1.2410e-03 \end{bmatrix} \tag{4.4}$$

With state vector

$$x = \begin{bmatrix} \alpha & (\text{deg}) \\ \theta & (\text{deg}) \\ q & (\text{deg/sec}) \\ u & (\text{ft/sec}) \end{bmatrix} \tag{4.5}$$

4.3.2 Stability Derivatives for a RSS Fighter Modern fighters are typically designed to be statically unstable and require the FCS to compensate for the airframe stability deficiencies. The static instability is a result of a center of gravity (cg) position near or aft of the aerodynamic center coupled with a reduced tail size. A RSS design offers performance advantages such as a higher load factor capability for a given engine thrust, reduced trim drag, and lower observables. The price for increased performance is often short-period divergence. Also, low levels of short-period damping may accompany tail size reductions. When designing a FCS for a RSS aircraft, the most obvious stability derivatives to augment are those that cause the trouble in the first place, M_q and M_α, to improve damping and stability, respectively [MJM86, p.531]. These are also the stability derivatives to alter to do just the opposite, destabilize the NT-33A to get a RSS airframe. In arriving at a RSS aircraft, only three of the NT-33A's moment stability derivatives need altering. The X and Z force stability derivatives will not be modified, consistent with the previous discussion on simulation limitations.

To simulate an aft cg, M_α is chosen to be a small and positive. The short period roots are (to a good approximation) the eigenvalues of Eqn 2.11.

$$s = \frac{(M_q + M_{\dot\alpha} + Z_w) \pm \sqrt{(M_q + M_{\dot\alpha} + Z_w)^2 - 4(M_q Z_w - M_\alpha)}}{2} \qquad \frac{1}{\text{sec}} \tag{4.6}$$

The short period roots are real when

$$(M_q + M_{\dot\alpha} + Z_w)^2 - 4(M_q Z_w - M_\alpha) \ge 0 \qquad \frac{1}{\text{sec}^2} \tag{4.7}$$

Fixing M_q, $M_{\dot{\alpha}}$, and Z_w at the NT-33A values and solving Eqn 4.7 for the M_α yields the approximate range of M_α for real short period roots

$$M_\alpha \geq -0.3855 \qquad \frac{1}{\sec^2} \tag{4.8}$$

One real root, $1/T_{sp_2}$, becomes unstable as M_α is increased. Choosing M_α small and positive will yield a RSS bare airframe.

To offset the larger than desired Z_w, both M_q, $M_{\dot{\alpha}}$ are reduced in magnitude. The similarities between M_q and $M_{\dot{\alpha}}$ can be seen looking at the theoretical aft horizontal tail contributions of C_{M_q} and $C_{M_{\dot{\alpha}}}$ listed in Table 4.2 [MAG73, p.292].

Table 4.2. Theoretical Aft Tail Contribution [MAG73, p.292]

Theoretical Aft Tail Contribution	
Derivative	Contribution
C_{M_α}	$-\frac{l_h}{c}\left[C_{L_{\alpha_h}} \frac{q_h}{q}\frac{S_h}{S}\left(1-\frac{\partial\varepsilon}{\partial\alpha}\right)\right]$
$C_{M_{\dot{\alpha}}}$	$-\frac{l_h}{c}\left[2C_{L_{\alpha_h}} \frac{q_h}{q}\frac{S_h}{S}\frac{l_h}{c}\frac{\partial\varepsilon}{\partial\alpha}\right]$
C_{M_q}	$-\frac{l_h}{c}\left[2C_{L_{\alpha_h}} \frac{q_h}{q}\frac{S_h}{S}\frac{l_h}{c}\right]$
$C_{M_{\delta_e}}$	$-\frac{l_h}{c}\left[C_{L_{\alpha_h}} \frac{q_h}{q}\frac{S_h}{S}\frac{\partial\alpha_h}{\partial\delta_e}\right]$

Noting tail size and location influence both C_{M_q} and $C_{M_{\dot{\alpha}}}$ similarly, Let

$$\tilde{M}_q = M_q + M_{\dot{\alpha}} \qquad \frac{1}{\sec} \tag{4.9}$$

For the NT-33A at this flight condition $M_{\dot{\alpha}} = -0.3084\ \sec^{-1}$ and $M_q = -0.9810\ \sec^{-1}$ and

$$M_{\dot{\alpha}} = 0.3144 M_q \qquad \frac{1}{\sec} \tag{4.10}$$

or alternatively

$$\tilde{M}_q = 1.3144 M_q \qquad \frac{1}{\text{sec}} \tag{4.11}$$

Substituting Eqn 4.11 in Eqn 4.6 yields

$$s = \frac{(\tilde{M}_q + Z_w) \pm \sqrt{(\tilde{M}_q + Z_w)^2 - 4(0.7608 \tilde{M}_q Z_w - M_\alpha)}}{2} \qquad \frac{1}{\text{sec}} \tag{4.12}$$

Once M_α is selected, Eqn 4.12 is a function of $\tilde{M}_q$ and Z_w *and* these two variables have *exactly* the same influence on the short period pole locations. The short period poles can be placed in representative locations by appropriate choice of $\tilde{M}_q$ (since Z_w can't be altered). A reasonable level of instability can be realized by choosing M_α small and positive, say

$$M_{\alpha_{fighter}} = -0.05 M_{\alpha_{NT-33A}} = 4.4734\text{e}-01 \qquad \frac{1}{\text{sec}^2} \tag{4.13}$$

As was shown in Table 4.1, Z_w for the NT-33A was on the average over thirty percent higher than desired for simulation of a fighter. Also, data from Table 4.1 indicate Eqn 4.10 is approximately correct for modern fighters and that $\tilde{M}_{q_{NT-33A}} \cong 2.5 \tilde{M}_{q_{fighter}}$. To offset the higher than desired Z_w and to simulate a reduced tail size and location, both M_q and $M_{\dot{\alpha}}$ are reduced substantially[5]

$$\begin{aligned} M_{q_{fighter}} &= 0.3 M_{q_{NT-33A}} = -2.9430\text{e}-01 \qquad \frac{1}{\text{sec}} \\ M_{\dot{\alpha}_{fighter}} &= 0.3 M_{\dot{\alpha}_{NT-33A}} = -9.2520\text{e}-01 \qquad \frac{1}{\text{sec}} \end{aligned} \tag{4.14}$$

When these stability derivatives are substituted in Eqn 2.7, the resulting A and B matrices are

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[5] M_α is also affected by downsizing the tail, however, the cg location is the major factor influencing the magnitude and sign of M_α.

$$A_{fighter} = \begin{bmatrix} -1.2488e+00 & 0 & 1 & -1.2498e-02 \\ 0 & 0 & 1 & 0 \\ 5.6287e-01 & 0 & -3.8682e-01 & -2.1887e-02 \\ 2.1652e-01 & -5.6200e-01 & 0 & -8.5402e-03 \end{bmatrix} \tag{4.15}$$

$$B_{fighter} = \begin{bmatrix} -7.1760e-02 \\ 0 \\ -1.4193e+01 \\ -1.2410e-03 \end{bmatrix} \tag{4.16}$$

The eigenvalues of $A_{fighter}$ are

$$\begin{aligned} \frac{1}{T_{sp_1}} &= -1.6832e+00 \quad \frac{\text{rad}}{\text{sec}} \\ \frac{1}{T_{sp_2}} &= +2.3536e-01 \quad \frac{\text{rad}}{\text{sec}} \\ \lambda_p &= -9.8172e-02 \pm j1.9778e-01 \quad \frac{\text{rad}}{\text{sec}} \end{aligned} \tag{4.17}$$

The unstable pole, $1/T_{sp_2}$, has a time to double amplitude of

$$t_2 = \frac{\ln 2}{0.23536} = 6.13 \text{ sec} \tag{4.18}$$

For comparison, worst case scenario values of t_2 for the F-16, X-29, and X-31 are on the order of 1.5, 0.15, and 0.2 seconds, respectively [AGA91, p.11, 3, 14].

This simulated RSS fighter was determined from a stability derivative approach. However, the NT-33A uses response feedback to simulate other aircraft and so it is necessary to determine the feedback gains required to approximate this RSS fighter.

4.3.3 Calculation of VSS Gains Without Actuation If perfect actuation is assumed, the feedback gains required to simulate the RSS fighter can be calculated algebraically. Since the NT-33A uses very fast actuators, $\omega_n = 63$ rad/sec, this first cut is a very good approximation. To perform the calculation it's convenient to rewrite Eqn 2.7 using lumped moment stability derivatives

$$\begin{bmatrix}\dot{\alpha}\\ \dot{\theta}\\ \dot{q}\\ \dot{u}\end{bmatrix}=\begin{bmatrix}Z_w & 0 & 1 & \frac{Z_u}{U_0}\\ 0 & 0 & 1 & 0\\ \hat{M}_\alpha & 0 & \hat{M}_q & \hat{M}_u\\ X_\alpha & -g & 0 & X_u\end{bmatrix}\begin{bmatrix}\alpha\\ \theta\\ q\\ u\end{bmatrix}+\begin{bmatrix}\frac{Z_{\delta_e}}{U_0}\\ 0\\ \hat{M}_{\delta_e}\\ X_{\delta_e}\end{bmatrix}[\delta_e] \tag{4.19}$$

where

$$\begin{aligned}\hat{M}_\alpha &= M_\alpha + M_{\dot{\alpha}}\frac{Z_\alpha}{U_0}\\ \hat{M}_q &= M_q + M_{\dot{\alpha}}\\ \hat{M}_u &= M_u + \frac{M_{\dot{\alpha}}}{U_0}Z_u\\ \hat{M}_{\delta_e} &= M_{\delta_e} + \frac{M_{\dot{\alpha}}}{U_0}Z_{\delta_e}\end{aligned} \tag{4.20}$$

The NT-33A VSS simulates the desired short period dynamics of the RSS fighter through blended feedback of α and q (with appropriate gains) to the elevator[6]. Since these are the only two feedbacks used, all four rigid body poles cannot be placed. However, as will be seen later, the phugoid poles will remain roughly those of the NT-33A. Values for three of the four lumped moment stability derivatives, $\hat{M}_\alpha$, $\hat{M}_q$, and $\hat{M}_{\delta_e}$, are needed to algebraically calculate the feedback gains. The values for these stability derivatives for both the RSS fighter and the NT-33A are listed in Table 4.3.

Table 4.3. Lumped Moment Stability Derivatives

Lumped Moment Stability Derivatives		
Derivative	RSS Fighter	NT-33A
$\hat{M}_\alpha$	+5.6287e−01	−8.5615e+00
$\hat{M}_q$	−3.8682e−01	−1.2894e+01
$\hat{M}_{\delta_e}$	−1.4178e+01	−1.4178e+01

[6]Other feedbacks can also be used, but these two will suffice.

The feedback gains, $K_\alpha = \delta_e/\alpha$, and $K_q = \delta_e/q$ are calculated using

$$\begin{bmatrix} K_\alpha & K_q \end{bmatrix} = \begin{bmatrix} \hat{M}_{\delta_{e_{NT-33A}}} \end{bmatrix}^{-1} \begin{bmatrix} \Delta\hat{M}_\alpha & \Delta\hat{M}_q \end{bmatrix} \tag{4.21}$$

where

$$\begin{aligned} \Delta\hat{M}_\alpha &= \hat{M}_{\alpha_{fighter}} - \hat{M}_{\alpha_{NT-33A}} \\ \Delta\hat{M}_q &= \hat{M}_{q_{fighter}} - \hat{M}_{q_{NT-33A}} \end{aligned} \tag{4.22}$$

Substituting values from Table 4.3 into Eqn 4.21 gives

$$\begin{aligned} \begin{bmatrix} K_\alpha & K_q \end{bmatrix} &= \begin{bmatrix} -1.4178e+01 \end{bmatrix}^{-1} \begin{bmatrix} 9.1244e+00 & 9.0258e-01 \end{bmatrix} \\ &= \begin{bmatrix} -6.4356e-01 \ \dfrac{\text{deg}}{\text{deg}} & -6.3661e-02 \ \dfrac{\text{deg}}{\frac{\text{deg}}{\text{sec}}} \end{bmatrix} \end{aligned} \tag{4.23}$$

These gains were verified using a simple SIMULINK model of the NT-33A VSS. The algebraically determined feedback gains give the following pole locations

$$\begin{aligned} \frac{1}{T_{sp_1}} &= -1.6503e+00 \quad \frac{\text{rad}}{\text{sec}} \\ \frac{1}{T_{sp_2}} &= +2.3229e-01 \quad \frac{\text{rad}}{\text{sec}} \\ \lambda_p &= -8.9992e-02 \pm j1.8986e-01 \quad \frac{\text{rad}}{\text{sec}} \end{aligned} \tag{4.24}$$

Which are close to the eigenvalues obtained when substituting the RSS fighter stability derivatives into Eqn 2.7 (i.e. Eqn 4.17). The feedback gains can be adjusted until the short period poles are the same as Eqn 4.17. Accurate feedback gains can be determined by including the actuator dynamics when accomplishing these final adjustments.

4.3.4 Determination of VSS Gains With Actuation Incorporating an actuator model slightly changes the pole locations for both the actuator and the simulated RSS fighter. Some minor adjustments to the feedback gains essentially yields the desired RSS fighter. Choosing the following feedback gains

$$
\begin{aligned}
K_{\alpha} &= -6.3000e-01 \quad \frac{\text{deg}}{\text{deg}} \\
K_{q} &= -7.8000e-02 \quad \frac{\text{deg}}{\frac{\text{deg}}{\text{sec}}}
\end{aligned}
\tag{4.25}
$$

results in the following pole locations for the RSS fighter

$$
\begin{aligned}
\frac{1}{T_{sp_1}} &= -1.6816e+00 \quad \frac{\text{rad}}{\text{sec}} \\
\frac{1}{T_{sp_2}} &= +2.3502e-01 \quad \frac{\text{rad}}{\text{sec}} \\
\lambda_p &= -7.7721e-02 \pm j1.8011e-01 \quad \frac{\text{rad}}{\text{sec}}
\end{aligned}
\tag{4.26}
$$

The high frequency actuator poles migrate a negligible amount. Figure 4.2 depicts a root locus diagram for the NT-33A VSS inner loop (RSS fighter poles marked with + signs).

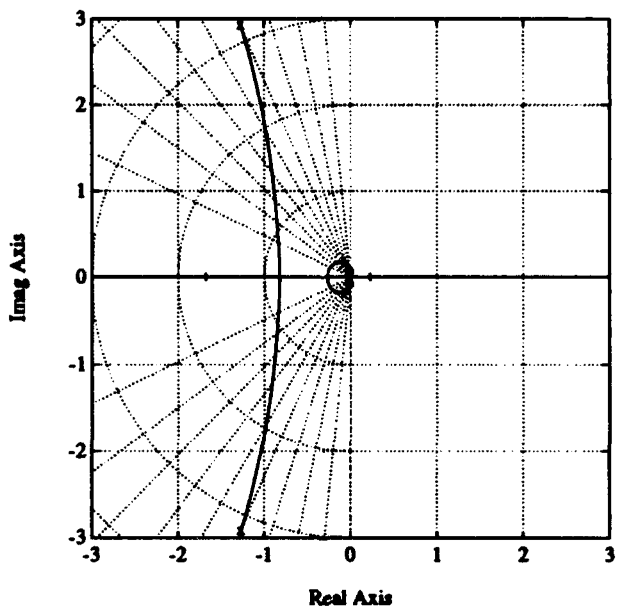

Figure 4.2. NT-33A VSS Root Locus

4.4 *Superaugmented Flight Control System*

Control system characteristics of superaugmented aircraft are discussed in detail in [MMJ84]. Figure 4.3 shows the basic flight control system architecture for the

superaugmented flight control system. To keep the architecture as simple as possible, turn compensation was not incorporated into the configurations in this experiment. The approach taken here is to first determine realistic values for the loop gain and FCS zero location so as to satisfy MIL-F-87242 gain and phase margin requirements. Next, the handling qualities implications of changes to the loop gain, FCS zero location, and selected prefilters are determined in terms of the Bandwidth and Dropback criterions.

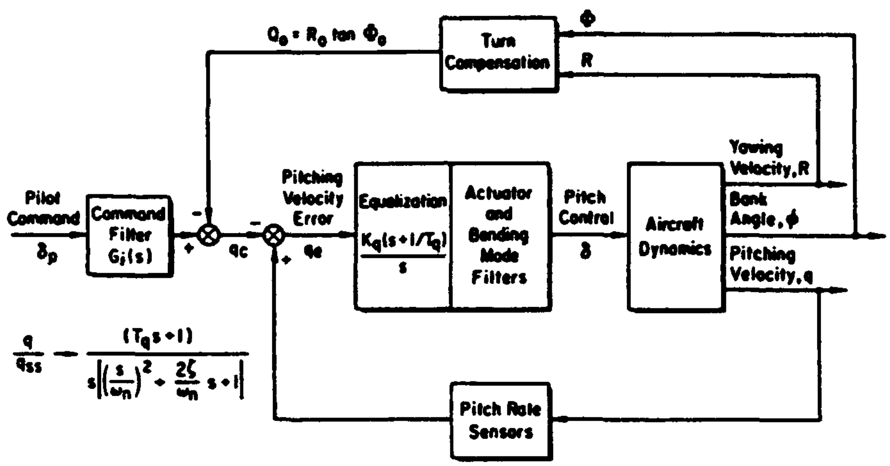

Figure 4.3. The Superaugmented Flight Control System [MMJ84, p.19]

4.4.1 Flight Control System Stability Margins Basic flight control system characteristics were determined by breaking the pitch rate feedback loop and applying classic open loop analysis techniques. The primary effect of increasing the loop gain, K_q, and the FCS zero location, $1/T_q$, can be seen clearly in Figure 4.4. Figure 4.4 depicts five root loci of $-q/q_e$ corresponding to five $1/T_q$ locations from 2 to 4 rad/sec. The unstable pole, $1/T_{sp_2}$, quickly restablizes as K_q, increases effectively canceling the low frequency pitch attitude zero, $1/T_{\theta_1}$. The stable pole, $1/T_{sp_1}$, approaches the high frequency pitch attitude zero, $1/T_{\theta_2}$, resulting in a near pole zero cancellation. The phugoid poles circle around the FCS zero, $1/T_q$, and become the dominant second order mode.

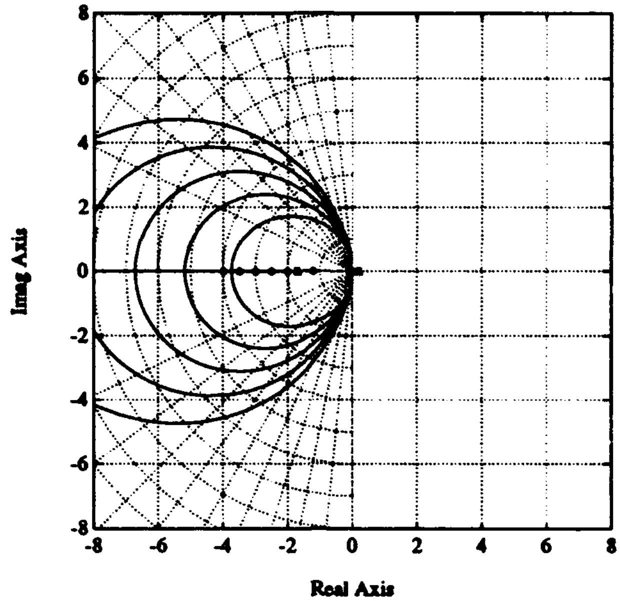

Figure 4.4. Superaugmented Pitch Rate Loop Root Loci

A typical Bode plot for $-q/q_e$ is depicted in Figure 4.5.

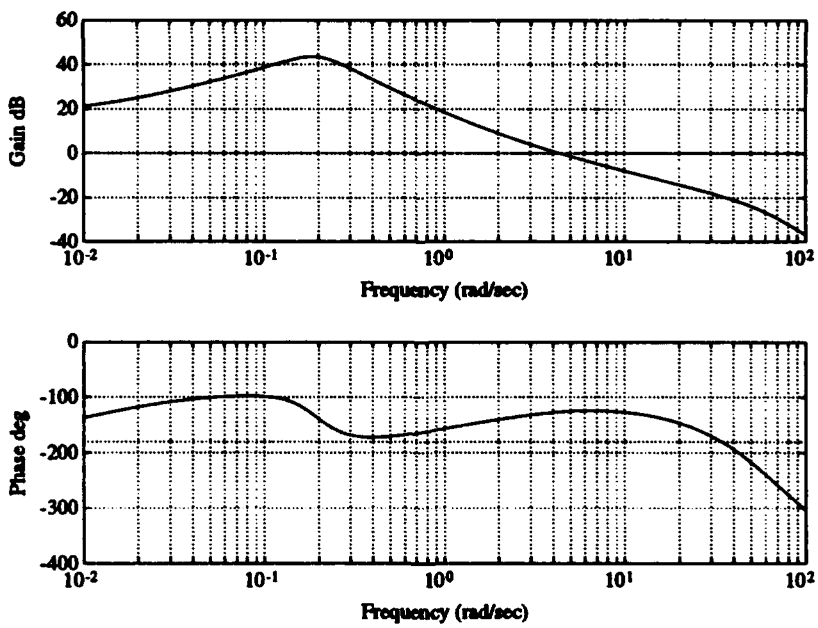

Figure 4.5. Superaugmented Pitch Rate Loop Bode Plot (Typical)

Basic flight control system stability characteristics were determined as a function of K_q, and $1/T_q$ by systematically varying these two parameters over a range that would

satisfy MIL-F-87242 gain and phase margin requirements. The applicable gain and phase margin requirements from [MIL86, p.106] are a gain margin (GM) of ±6 dB and phase margin (PM) of ±45°. The upper and lower gain margins are depicted in Figure 4.6. The upper gain margin is essentially independent of $1/T_q$, whereas the lower gain margin depends on $1/T_q$. The left end of each curve corresponds to the K_q required for 45° phase margin and the right end of each curve corresponds to the K_q that achieves maximum phase margin. The gain margin requirements are more than satisfied for any value of K_q that would satisfy the phase margin requirements.

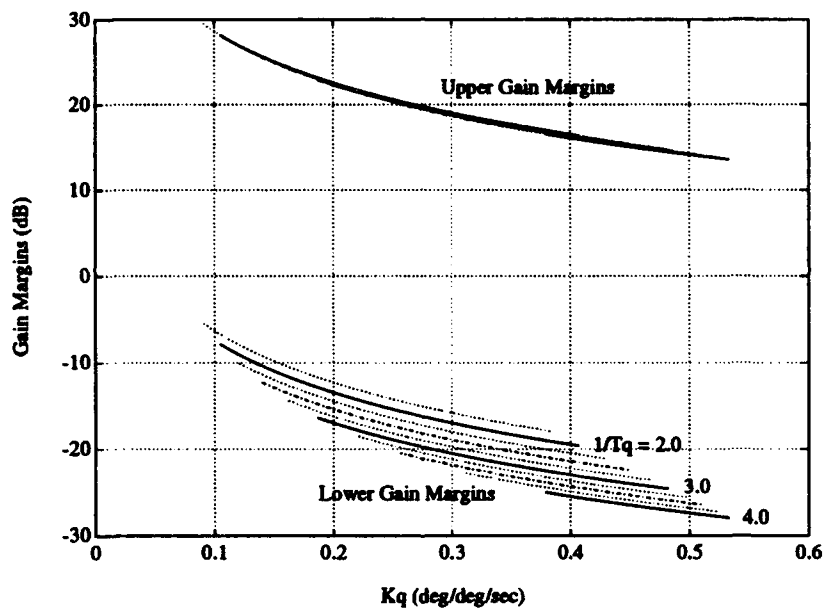

Figure 4.6. Superaugmented Pitch Rate Loop Upper and Lower Gain Margins[7]

Phase margin as a function of K_q and $1/T_q$ is depicted in Figure 4.7. The right edge of each curve corresponds to the K_q that achieves maximum phase margin. There is a practical upper limit of approximately 4.0 rad/sec for $1/T_q$ to meet MIL-F-87242 phase

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[7] $1/T_q$ was varied from 1.75 to 4.0 rad/sec every 0.25 rad/sec as indicated by the dashed lines.

margin requirements. Phase margin requirements drive the range of acceptable K_q and $1/T_q$ for a practical design.

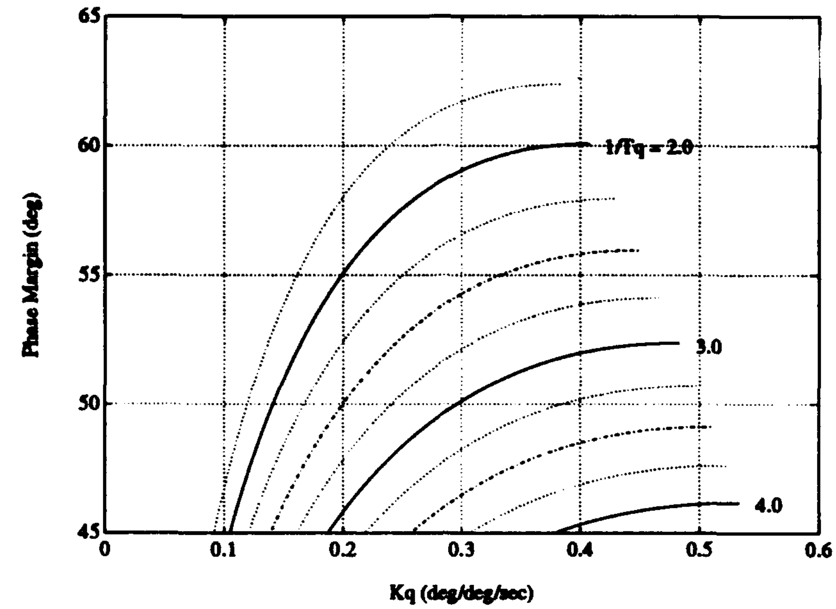

Figure 4.7. Superaugmented Pitch Rate Phase Margin

4.4.2 Flight Control System Dominant Second Order Roots The effective damping ratio, ζ', as a function of K_q and $1/T_q$ is depicted in Figure 4.8. The lower edge of each curve represents the K_q for 45° phase margin and the upper right edge of each curve represents the K_q for maximum phase margin. The minimum ζ' for a practical design is approximately $\zeta' = 0.6$. A damping ratio of $\zeta' = 0.7$ will work for any value of $1/T_q$ between 1.75 and 4.0 rad/sec.

The location of the dominant second order roots as a function of K_q and $1/T_q$ is depicted in Figure 4.9 in terms of an effective damping ratio, ζ', and an effective natural frequency, ω'. The left edge of each curve represents the K_q for 45° phase margin and the right edge of each curve represents the K_q for maximum phase margin.

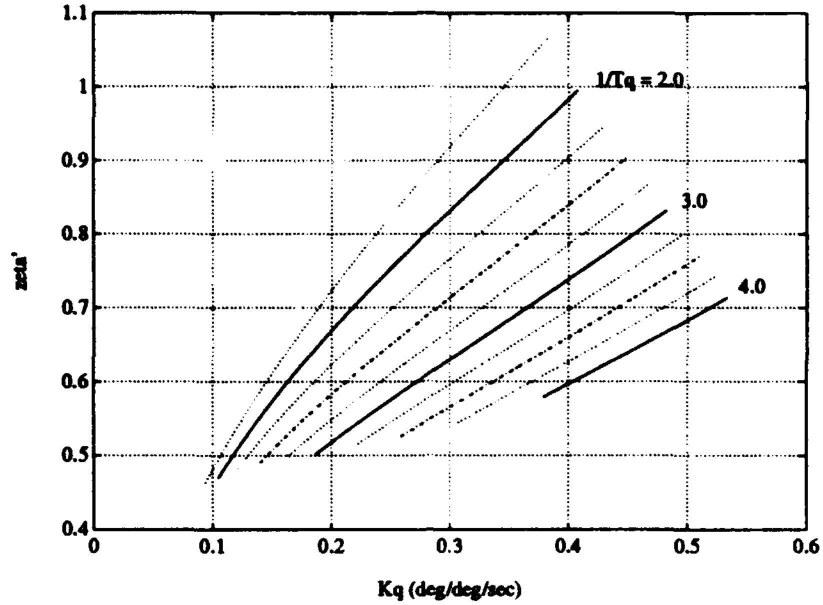

Figure 4.8. Superaugmented Effective Damping Ratios

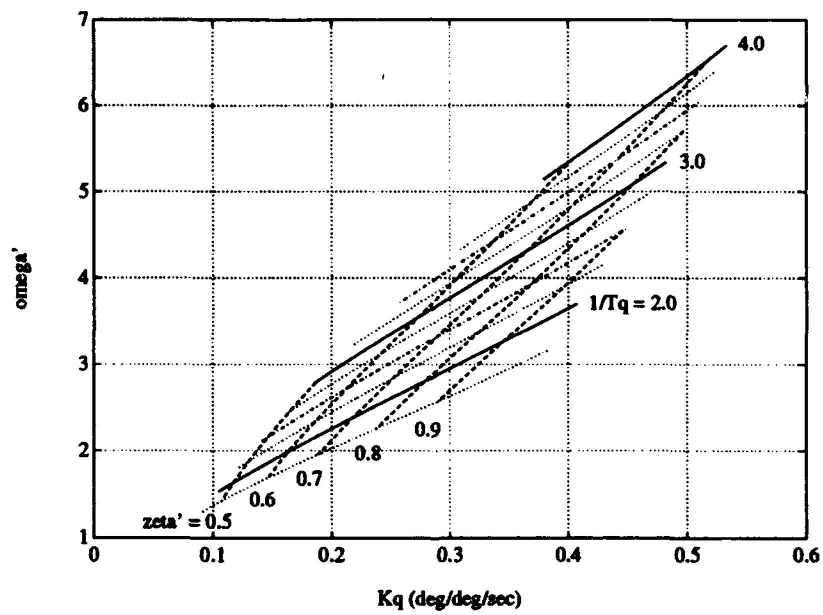

Figure 4.9. Superaugmented Dominant Second Order Roots

The combinations of K_q and $1/T_q$ that will achieve a practical pitch rate loop have been identified. Next, the handling qualities implications of several prefilters to shape the pilot's stick force input will be examined.

4.5 Handling Qualities Predictions for RCAH and ACAH Response-Types

The Bandwidth criterion and Dropback criterion parameters were determined as functions of K_q and $1/T_q$ and selected pilot command input shaping prefilters. The prefilters were used to tailor the effective vehicle dynamics so as to achieve pure RCAH, RCAH extended bandwidth (pseudo conventional), and ACAH response-types. The RCAH prefilter is

$$G(s) = 1 \tag{4.27}$$

The RCAH extended bandwidth response-type prefilter is

$$G(s) = \frac{\left(s + \frac{1}{T_1}\right)}{\left(s + \frac{1}{T_q}\right)} \tag{4.28}$$

Where $1/T_1 < 1/T_q$ (lead compensation). As $1/T_1 \rightarrow 1/T_{\theta_2}$ the response-type is pseudo conventional. The ACAH prefilter is

$$G(s) = \frac{s}{\left(s + \frac{1}{T_q}\right)} \tag{4.29}$$

Since by definition, the ACAH response-type drops all the way back to the trim attitude once the control is released, the Dropback criterion doesn't apply for this response-type. For all the figures in this section, K_q was varied to keep $45° \leq \Phi \leq \Phi_{max}$, and the FCS zero, $1/T_q$, was varied from 1.75 to 4.0 rad/sec every 0.25 rad/sec with intermediate values indicated by dashed lines. For convenience, lines of constant ω' are depicted as dashed lines on the crossplots of flight path bandwidth vs. pitch attitude bandwidth.

4.5.1 Bandwidth Criterion Analysis The Bandwidth criterion parameters for RCAH, RCAH extended bandwidth, and ACAH response-types were determined by varying K_q, $1/T_q$, and the selected pilot command input shaping prefilter.

Figure 4.10 depicts the phase delay parameter vs. the pitch attitude bandwidth for RCAH response-types. Both the pitch attitude bandwidth, ω_{BW_θ}, and phase delay parameter, τ_{p_θ}, are low for the RCAH response-types. Figure 4.11 depicts the flight path bandwidth, ω_{BW_γ} crossplotted with the pitch attitude bandwidth, ω_{BW_θ} for the RCAH designs. Both the pitch attitude bandwidth, ω_{BW_θ}, and the flight path bandwidth, ω_{BW_γ}, are low for the RCAH response-types with ω_{BW_γ} approaching a limiting value of approximately 1.15 rad/sec. Every Level 1 conventional response-type from the Calspan experiment had a greater flight path bandwidth than this. The drawback of RCAH is reduced pitch attitude and flight path bandwidths.

Figure 4.12 depicts the phase delay parameter vs. pitch attitude bandwidth for RCAH extended bandwidth response-types (with $1/T_1 = 1/T_{\theta_2} = 1.25$ rad/sec depicted). For the RCAH response-types, the pitch attitude bandwidth, ω_{BW_θ}, now extends well into the Level 1 region and the phase delay parameter, τ_{p_θ}, remains low. Figure 4.13 depicts the flight path bandwidth, ω_{BW_γ} crossplotted with the pitch attitude bandwidth, ω_{BW_θ}, for the RCAH extended bandwidth designs. Both the pitch attitude bandwidth, ω_{BW_θ}, and the flight path bandwidth, ω_{BW_γ}, are now approximately the same as the Level 1 conventional response-types from the Calspan experiment. RCAH extended bandwidth response-types look very conventional in the region of piloted crossover.

Figure 4.14 depicts the phase delay parameter vs. pitch attitude bandwidth for ACAH. For the ACAH response-types, the pitch attitude bandwidth, ω_{BW_θ}, extends well into the Level 1 region and the phase delay parameter, τ_{p_θ}, remains low. Figure 4.15 depicts the flight path bandwidth, ω_{BW_γ} crossplotted with the pitch attitude bandwidth, ω_{BW_θ}, for the ACAH designs. For ACAH designs, the pitch attitude bandwidth, ω_{BW_θ}, is on the same order of magnitude as the Level 1 configurations from 1974, but the flight path bandwidth, ω_{BW_γ}, is higher than the Level 1 configurations from the Calspan experiment. These designs extend into the region where the lightly damped conventional response-types from the 1974 Calspan experiment were.

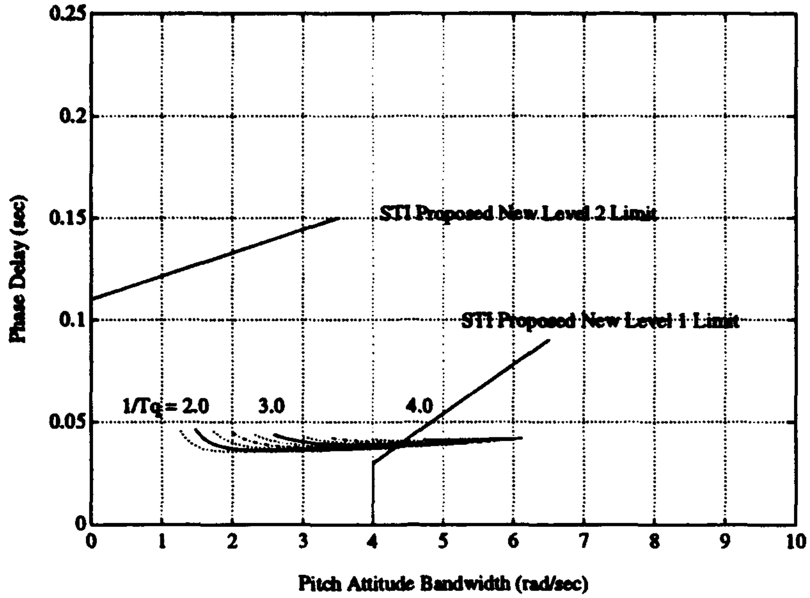

Figure 4.10. RCAH Bandwidth Criterion Analysis

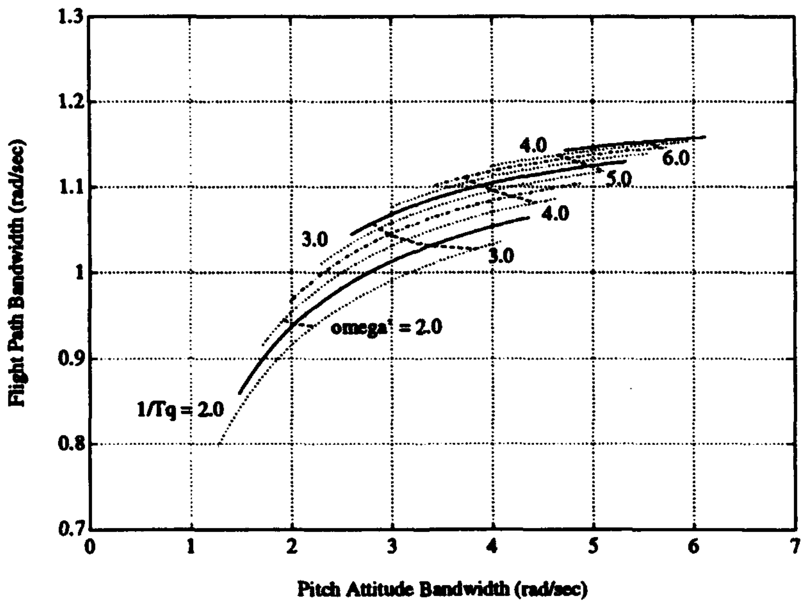

Figure 4.11. RCAH ω_{BW_γ} vs. ω_{BW_θ}

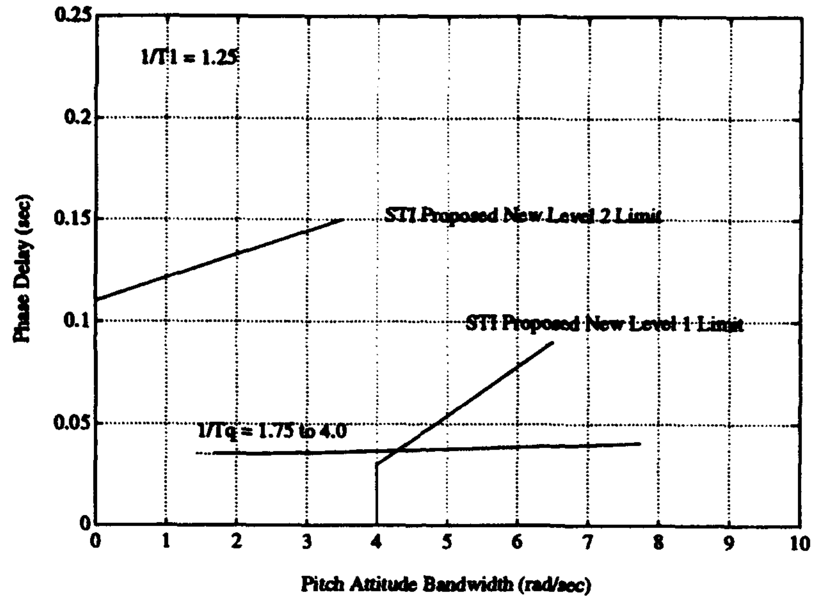

Figure 4.12. RCAH Extended Bandwidth, Bandwidth Criterion Analysis

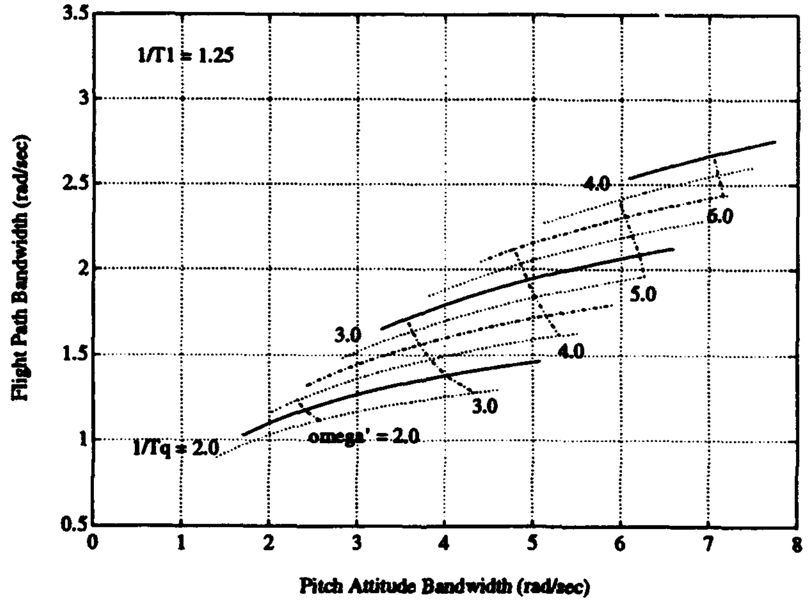

Figure 4.13. RCAH Extended Bandwidth ω_{BW_γ} vs. ω_{BW_θ}

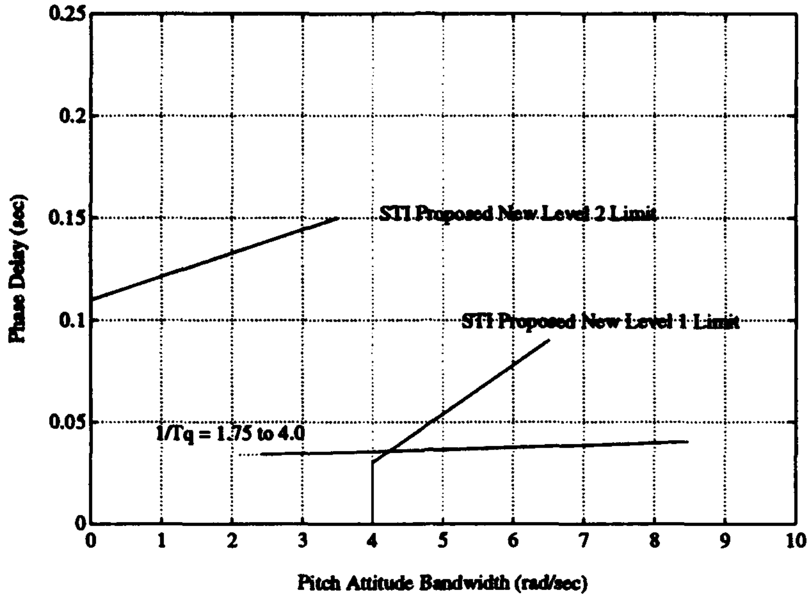

Figure 4.14. ACAH Bandwidth Criterion Analysis

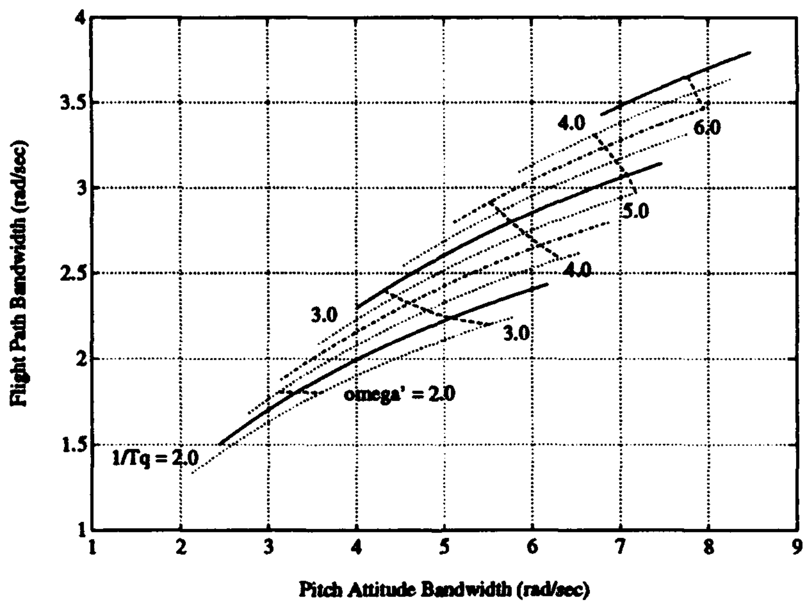

Figure 4.15. ACAH ω_{BW_γ} vs. ω_{BW_θ}

4.5.2 STI Dropback Criterion Analysis Figure 4.16 depicts the dropback trends for the RCAH and RCAH extended bandwidth response-types[8]. The dropback tendencies were determined using a boxcar input (10 lb step input held for 10 seconds followed by release to 0 lb). The steady state pitch rate, q_{ss}, was the value of q ten seconds after the 10 lb step input was applied and Drb was difference between the maximum value of θ and the value of θ ten seconds after release. In Figure 4.16, values for $1/T_1$ were varied every 0.25 rad/sec down to 0.75 rad/sec. Use of dashed lines for intermediate values of $1/T_1$ is analagous to that used for intermediate values of $1/T_q$.

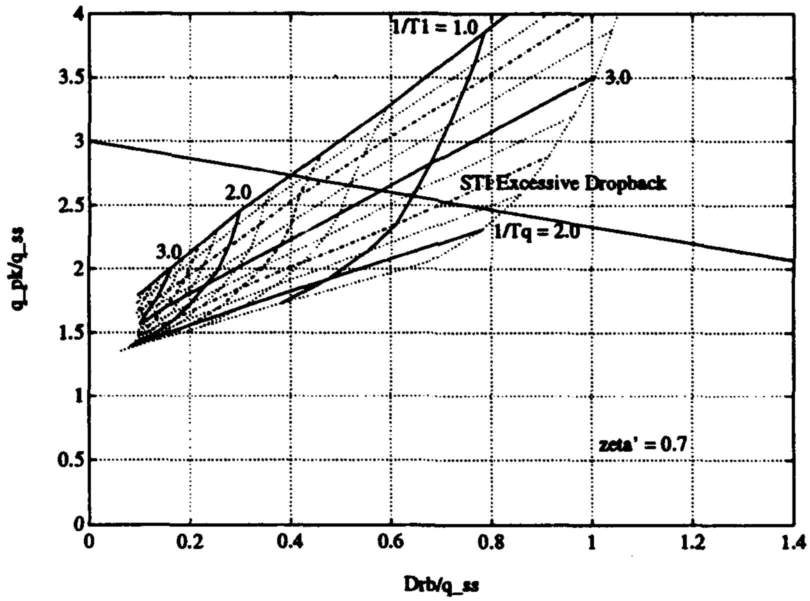

Figure 4.16. Dropback Trends for RCAH Response-Types

The dropback tendencies for the RCAH response-types are very low, approximately $q_{peak}/q_{ss} = 1.5$ and $Drb/q_{ss} = 0.1$. The dropback trends for the RCAH extended bandwidth designs show that as $1/T_1 \rightarrow 0$, $q_{ss} \rightarrow 0$ and so both $q_{peak}/q_{ss} \rightarrow \infty$ and $Drb/q_{ss} \rightarrow \infty$. This is as expected since in the limit as $1/T_1 \rightarrow 0$ an ACAH response-type is realized. However, as

[8]The effective damping was held constant at $\zeta' = 0.7$ for the cases depicted.

early as $1/T_1 = 1/T_{\theta_2}$ (the pseudo conventional response-type) the STI Dropback criterion predicts excessive dropback if $1/T_q \geq 3.25$. This prediction of poor handling qualities seems premature. It's not at all clear at what point the STI Dropback criterion can no longer be applied. There is no boundary between RCAH, RCAH extended bandwidth, and ACAH response-types in Figure 4.16. The transition from one response-type to another occurs gradually as the prefilter form is gradually changed. It seems very unlikely there will be a region of bad flying qualities encountered between RCAH extended bandwidth and ACAH.

The time domain based STI Dropback criterion, applicable for quasi open loop flying, appears to be of questionable value for predicting the mid-frequency abruptness tendencies of aircraft engaged in small amplitude compensatory tracking tasks. In Chapter 2, the literature review revealed a need for supplementing the Bandwidth criterion with the STI Dropback criterion to capture mid-frequency abruptness problems. In Chapter 3, a source of mid-frequency abruptness was traced to non K/s looking θ/F_{es} and γ/F_{es} transfer functions. These cases had excessive values of $|\theta/F_{es}|$ and $|\gamma/F_{es}|$ in the region of pilot crossover and could be identified by crossplotting $|\theta/F_{es}|_{\omega_{BW_\theta}}$ vs. ω_{BW_θ} and $|\lambda/F_{es}|_{\omega_{BW_\lambda}}$ vs. ω_{BW_γ}. Now, the STI Dropback criterion does not appear to emphasize the frequencies important for piloted loop closure. The Dropback criterion emphasizes low-frequency characteristics at the expense of the mid-frequency characteristics. Neither the Bandwidth criterion nor the STI Dropback criterion are functions of the selected command gain. The command gain is a *major* variable for control sensitivity. The Bandwidth criterion supplemented with more frequency response information in the region of piloted crossover appears to be a better approach for small amplitude compensatory tracking tasks.

V. *Pilot Evaluation Design*

5.1 Introduction

Pilot evaluation refers to the subjective assessment of aircraft handling qualities by pilots. The evaluation data consists generally of two parts: the pilot's commentary on the observations he made, and the rating(s) he assigns. Commentary and ratings are both important sources of information; they are the most important data on the closed-loop pilot-airplane combination which the engineer has [HC86, p.524].

The pilot evaluation was conducted by the HAVE GAS test team as part of a USAF TPS test management project (TMP). The test team consisted of two evaluation pilots (including the author), a navigator and a flight test engineer (FTE). Two Calspan instructor pilots with probe and drogue air refueling experience were the NT-33A safety pilots.

The test team designed the pilot evaluation experiment during the test management phase of TPS. First, specific flight test objectives were developed. Next, RCAH, ACAH, and conventional response-type configurations were chosen to meet those flight test objectives. For safety reasons, the configurations selected essentially covered the Level 1 and 2 bandwidth regions from the 1974 Calspan experiment[1]. Both evaluation pilots practiced probe and drogue air refueling in a NASA F-18B to become familiar with the task and to minimize the effect of a learning curve. The probe and drogue air refueling task was defined in accordance with NATOPS air refueling directives and specific performance criteria were established. A pilot comment card was developed and handling qualities, PIO, and turbulence rating scales selected to facilitate inflight data collection. Finally, the evaluation order was selected (by the project navigator and FTE) to expose the evaluation pilots to a

[1]Predicted Level 3 configurations were neither designed nor evaluated.

range of dynamics on consecutive evaluations and to minimize the effect of interpilot variability.

5.2 *Flight Test Objectives*

The general flight test objective was to qualitatively and quantitatively evaluate the suitability of selected RCAH, ACAH, and conventional response-types for probe and drogue air refueling to contribute to the research data base.

The specific flight test objectives were to:

1. Qualitatively and quantitatively evaluate the suitability of selected RCAH response-types for probe and drogue air refueling over a range of pitch attitude bandwidths from approximately 2.0 to 7.0 rad/sec and over a range of flight path bandwidths from approximately 1.0 to 3.0 rad/sec.

2. Qualitatively and quantitatively evaluate the suitability of selected ACAH response-types for probe and drogue air refueling over a range of pitch attitude bandwidths from approximately 3.0 to 7.0 rad/sec and over a range of flight path bandwidths from approximately 1.5 to 3.5 rad/sec.

3. Qualitatively and quantitatively evaluate the suitability of configuration C1X for the probe and drogue air refueling task. Configuration C1X replicates configuration 2A from the 1974 Calspan experiment. Configuration 2A was analyzed as a high dropback case and was rated Level 1 with pilot comments indicating pitch bobbling (evaluated only once).

4. Qualitatively and quantitatively compare the suitability of the best RCAH and ACAH configurations found during flight test with configuration C1. Configuration C1 replicates configuration 2D, one of the best conventional response-types from the 1974 Calspan experiment.

5.3 Configurations Evaluated

Fourteen configurations were selected for evaluation. Twelve configurations were unconventional response-types (RCAH and ACAH) and two were conventional response-types. For all the configurations, the analog NT-33A VSS was used to simulate a RSS fighter. The NT-33A digital FCS was then used to stabilize the simulated RSS fighter and achieve the desired response-type. Both the RCAH and ACAH response-types used q feedback and a proportional plus integral controller. The conventional response-types were realized by appropriate choice of α and q feedbacks. Detailed descriptions of the flight control systems for the fourteen configurations are given in Appendix E.

Four core configurations were combined with three different prefilter forms to generate the twelve unconventional response-types. The four core configurations were the low bandwidth RCAH configurations (R1 through R4). The other four RCAH configurations (R1X through R4X) incorporated an extended bandwidth prefilter to extend both the pitch attitude and flight path bandwidths. For these configurations, the FCS zero, $1/T_q$, was replaced with a prefilter zero, $1/T_1$, which was closer to the NT-33A high frequency pitch attitude zero, $1/T_{\theta_2}$. The ACAH configurations (A1 through A4) incorporated a washout prefilter to convert the pilot's stick force input from a rate command to an attitude command.

The two conventional response-type configurations (C1 and C1X) were designed to replicate configurations 2D and 2A, respectively, from the 1974 Calspan experiment. The core configuration (C1) was combined with an extended bandwidth prefilter to generate the other conventional response-type (C1X). The extended bandwidth prefilter not only extended the pitch attitude and flight path bandwidths, but also increased the dropback tendency to an excessive level.

For safety reasons, the RCAH, ACAH, and conventional response-type configurations were chosen to essentially cover the Level 1 and 2 bandwidth regions from the 1974 Calspan

experiment. The control sensitivities for all the configurations (except C1X) were selected by Calspan to hold $\dot{q}/F_{es}$ nearly constant among the configurations.

The Bandwidth criterion parameters for each of the HAVE GAS configurations are listed in Table 5.1.

Table 5.1. Bandwidth Criterion Parameters for HAVE GAS Configurations

Bandwidth Criterion Parameters for HAVE GAS Configurations					
Config	$\omega_{BW_{gain}}$ (rad/sec)	$\omega_{BW_{phase}}$ (rad/sec)	ω_{BW_θ} (rad/sec)	τ_{p_θ} (msec)	ω_{BW_γ} (rad/sec)
R1	3.32	2.51	2.51	77.4	0.98
R2	3.81	3.24	3.24	79.7	1.03
R3	4.16	3.97	3.97	82.2	1.06
R4	4.25	4.71	4.25	84.9	1.07
R1X	3.59	2.78	2.78	76.2	1.15
R2X	4.27	3.78	3.78	78.0	1.42
R3X	4.74	4.77	4.74	80.3	1.69
R4X	4.81	5.74	4.81	82.8	1.97
A1	—	3.72	3.72	74.7	1.99
A2	—	4.64	4.64	76.7	2.40
A3	—	5.56	5.56	79.0	2.80
A4	—	6.47	6.47	81.6	3.17
C1	4.85	4.67	4.67	77.1	1.76
C1X	5.72	5.86	5.72	74.7	2.66

For all the configurations, the qualitative effect of the addition of filters in the command path was an increase in phase delay and a reduction in pitch attitude bandwidth. The reduction in bandwidth was most severe for the higher bandwidth, gain margin limited configurations (R4, and R4X). Two other configurations (R3X and C1X) were also gain margin limited, however, for these configurations, $\omega_{BW_\theta} = \omega_{BW_{gain}} \cong \omega_{BW_{phase}}$.

Dropback criterion and control sensitivity parameters for the HAVE GAS configurations are listed in Table 5.2. Crossplots of the control sensitivity parameters and bandwidths will be shown in Chapter 6 along with the handling qualities ratings assigned.

Table 5.2. Control Sensitivity Parameters for HAVE GAS Configurations

Control Sensitivity Parameters for HAVE GAS Configurations						
Config	q_{pk}/q_{ss} (—)	Drb/q_{ss} (sec)	F_{es}/n (lb/ g)	$\dot{q}/F_{es}$ (deg/lb - sec^2)	$\lvert\theta/F_{es}\rvert_{\omega_{BW_\theta}}$ (dB)	$\lvert\gamma/F_{es}\rvert_{\omega_{BW_\gamma}}$ (dB)
R1	1.30	0.27	2.1	6.21	0.37	5.01
R2	1.31	0.21	3.6	4.83	–6.04	–0.42
R3	1.33	0.17	4.5	4.90	–9.38	–2.81
R4	1.36	0.14	6.1	4.36	–12.34	–5.64
R1X	1.47	0.40	3.2	5.30	–2.55	0.67
R2X	1.70	0.43	5.3	5.09	–7.72	–5.84
R3X	1.99	0.46	7.0	5.68	–10.24	–10.01
R4X	2.34	0.48	10.0	5.59	–11.86	–14.40
A1	—	—	—	8.42	–2.42	–2.41
A2	—	—	—	7.11	–7.14	–9.07
A3	—	—	—	5.41	–11.98	–15.64
A4	—	—	—	3.70	–17.04	–22.27
C1	—	—	7.1	6.11	–9.42	–9.37
C1X	—	—	7.1	13.26	–5.80	–9.93

5.4 Evaluation Pilots

Two USAF TPS student pilots evaluated the fourteen configurations for suitability in the probe and drogue air refueling task. Their backgrounds were:

<u>Pilot A</u>

USAF Captain and senior pilot with over 2,400 hours flying time, primarily in high performance aircraft. Flying experience includes 1,500 hours as a T-38A instructor pilot and

flight examiner and 650 hours as an F-16 fighter pilot. Gained extensive experience with boom air refueling during Operation Desert Storm.

Pilot B

USAF Captain and senior pilot with over 2,800 hours flying time, primarily in high performance aircraft. Flying experience includes 1,800 hours as a T-38A instructor pilot and flight examiner and 750 hours as an F-15 fighter pilot. Gained extensive experience with boom air refueling during numerous ocean crossings and participation in Operation Desert Storm.

Prior to the evaluation, both pilots received a training flight in a NASA F-18B and were qualified to NATOPS standards for day probe and drogue air refueling. This training familiarized the pilots with the task, minimized the effect of a learning curve, and provided experience for choosing performance criteria.

5.5 *Task Definition and Performance Criteria*

5.5.1 Probe and Drogue Air Refueling Task The task was defined in accordance with NATOPS air-to-air refueling manual guidance for refueling from tactical tankers [NAV92, p.5]. Refueling procedures were to move into the precontact position (10 to 20 ft behind and slightly below the drogue). Observe the amber light on the air refueling store (ARS) indicating the drogue may be engaged. Establish a 3 to 5 knot closure speed. After engaging the drogue, continue to push the hose in until the amber light extinguished (about 5 to 8 ft). To disengage from the drogue, return the drogue to the position at which it was first engaged and then establish a slow opening rate by reducing power.

Aerial refueling hazards were minimized by aborting an attempt if any of the hazards listed in air-to-air refueling manual [NAV92, p.6] developed. An approach to the drogue was aborted if the closure rate stopped or exceeded 5 knots, if the probe tip passed beyond the

edge of the drogue, if the probe tipped the basket, or any time safety of flight was jeopardized.

5.5.2 Task Performance Criteria Specific task performance criteria were established to characterize desired and adequate performance. The goal for each evaluation was a minimum of three engagements. This allowed enough time to become familiar with each configuration prior to rating it. No maximum number of attempts were specified. Based on the experience gained in the NASA F-18B, and on inputs from operational pilots with probe and drogue air refueling experience, desired performance was defined as a 50 percent (or greater) success rate and adequate performance as 25 percent (or greater) success rate for engaging the drogue. Additionally, desired performance could not be compromised by undesirable PIO tendencies nor could adequate performance include any divergent aircraft motions. These last criteria were specified in terms of PIORs using the PIO tendency rating scale (discussed in the next section). The task performance criteria are summarized in Table 5.3.

Table 5.3. Probe and Drogue Air Refueling Task Performance Criteria

Probe and Drogue Air Refueling Task Performance Criteria		
Performance Criteria	Number of Attempts Required to Complete 3 Hookups	Maximum Allowable PIO Tendency Rating
Desired	≤ 6	2
Adequate	7–12	4

5.6 Pilot Comment Card and Rating Scales

5.6.1 Pilot Comment Card Comment data are the backbone of the evaluation experiment. Pilot comments can tell the analyst not only that something is wrong, but also where system changes can be made to improve handling qualities. Pilot comment data were standardized through the use of a pilot comment card. The pilot comment card, shown in Figure 5.1, was really a questionnaire to facilitate inflight data collection. It ensured that all

important or suspected aspects were considered and the reason for a given rating was specified. The pilot comment card also provided an understanding for the tradeoffs with which pilots must continually contend, and stimulated comments that might not otherwise be offered.

Pilot Comment Card
I. Pilot Rating (Cooper-Harper Scale) a) Desired performance? If no, what prevented it? b) Adequate performance? If no, what prevented it? c) Was primary problem (if any) in the longitudinal axis or the lat/dir axes? II. Pitch Control During Approach to Basket a) Undesirable motions? b) Predictability? c) Initial response: too quick / too slow? d) Does aggressiveness affect handling qualities? e) Are you having to compensate? III. Feel System a) Forces: too high / too low? b) Stick deflection: too much / too little? c) Breakout: too much / too little? IV. PIO Tendency Rating V. Turbulence Rating VI. Other a) Did lat/dir characteristics detract from pitch response? b) Was the drogue stable? VII. Want to change your C-H rating?

Figure 5.1. Pilot Comment Card

After completing a minimum of three engagements, the NT-33A was returned to a trail position, control was transferred to the safety pilot, and each item on the pilot comment card was addressed by the evaluation pilot. Additional comments were gathered during the post flight debriefing with either the project FTE or navigator.

5.6.2 Rating Scales The pilot rating is the other necessary ingredient in pilot evaluation. It is the end product of the evaluation process, giving weight to each of the good and bad features as they relate to the intended use of the aircraft and quantifying the overall quality [HC86, p.524]. The Cooper-Harper rating scale, Figure 5.2, has been accepted as the standard measure of quality during pilot evaluations and was chosen for this experiment.

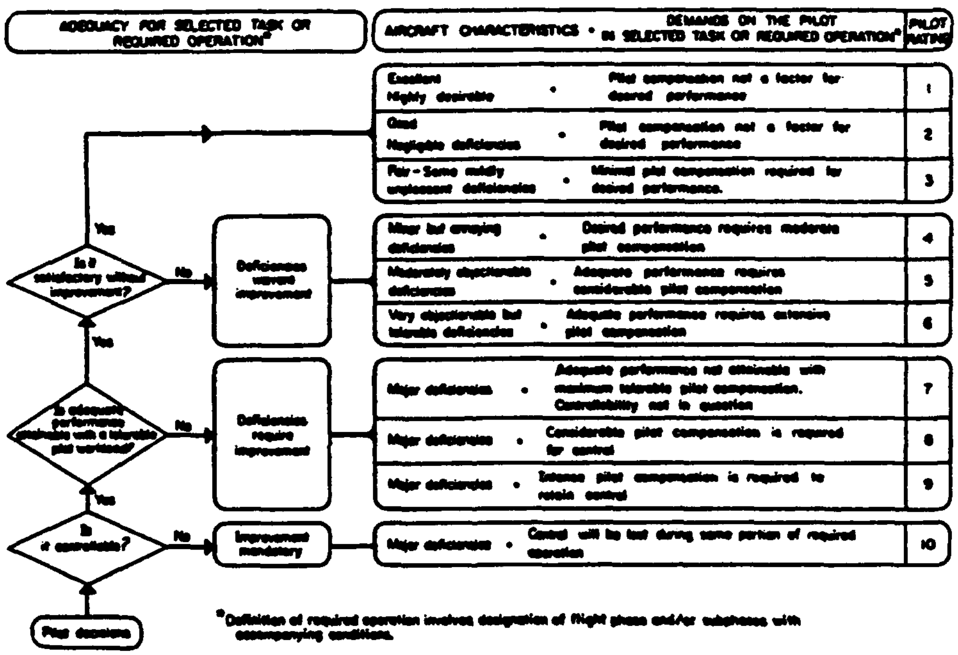

Figure 5.2 Cooper-Harper Rating Scale [CH69, p.12]

The Cooper-Harper rating scale has a decision tree structure. The evaluation pilot answers a series of yes-no questions which leads to a choice of one among three ratings. The decisions are fundamental to the attainment of meaningful, reliable, and repeatable ratings.

These decisions, and in fact, the use of the whole scale, depend on the precise definition of the words used. Table 5.4 is a partial list of the most applicable Cooper-Harper rating scale definitions from the original NASA technical note [CH69].

Table 5.4. Cooper-Harper Rating Scale Definitions [CH69, p.30-33]

Cooper-Harper Rating Scale Definitions	
Description	**Definition**
Compensation	The measure of additional pilot effort and attention required to maintain a given level of performance in the face of deficient vehicle characteristics.
Handling Qualities	Those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role.
Mission	The composite of pilot-vehicle functions that must be performed to fulfill operational requirements. May be specified for a role, complete flight, flight phase, or flight subphase.
Performance	The precision of control with respect to aircraft movement that a pilot is able to achieve in performing a task (Pilot-vehicle performance is a measure of handling performance. Pilot performance is a measure of the manner in which a pilot moves the principal controls in performing a task).
Role	The function or purpose that defines the primary use of an aircraft.
Task	The actual work assigned a pilot to be performed in completion of or as representative of a designated flight segment.
Workload	The integrated physical and mental effort required to perform a specified piloting task.

Other rating scales were also used to classify pilot comments pertaining to specific characteristic such as PIO tendency and turbulence. Table 5.5 is the PIO rating scale used and Figure 5.3 is the abbreviated decision tree version used inflight.

Table 5.5. PIO Tendency Rating Scale [MIL90, p.322]

PIO Tendency Rating Scale	
Description	**Rating**
No tendency for pilot to induce undesirable motions.	1
Undesirable motions tend to occur when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated by pilot technique.	2
Undesirable motions easily induced when pilot initiates abrupt maneuvers or attempts tight control. These motions can be prevented or eliminated but only at sacrifice to task performance or through considerable pilot attention and effort.	3
Oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must reduce gain or abandon task to recover.	4
Divergent oscillations tend to develop when pilot initiates abrupt maneuvers or attempts tight control. Pilot must open loop by releasing or freezing the stick.	5
Disturbance or normal pilot control may cause divergent oscillation. Pilot must open control loop by releasing or freezing the stick.	6

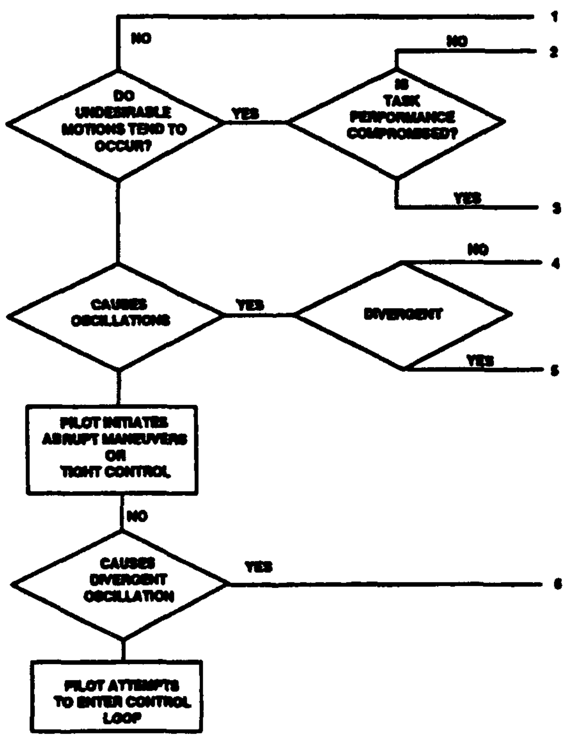

Figure 5.3. PIO Tendency Rating Scale [MIL90, p.152]

Because turbulence can be an important factor, the effect of turbulence on task performance was also recorded. Table 5.6 is the turbulence effect rating scale used.

Table 5.6 Turbulence Effect Rating Scale [BCC74, p.27]

Turbulence Effect Rating Scale		
Increase of Pilot Effort with Turbulence	Deterioration of Task Performance with Turbulence	Rating
No Significant Increase	No Significant Deterioration	A
More Effort Required	No Significant Deterioration	B
	Minor	C
	Moderate	D
Best Efforts Required	Moderate	E
	Major (But Evaluation Tasks Can Still be Accomplished)	F
	Large (Some Tasks Cannot be Performed)	G
Unable to Perform Tasks		H

5.7 Evaluation Procedures

5.7.1 Flight Condition The desired flight condition for all evaluations was 10,000 ft pressure altitude (PA) and 250 KIAS ($n/\alpha \cong 18\ g/\text{rad}$). This flight condition was essentially the same used during the 1974 Calspan experiment. Most of the flight testing took place at this desired flight condition, however, altitude was adjusted as necessary between 9,500 ft PA and 14,500 ft PA to avoid weather and turbulence when required. All evaluations were conducted at the center gravity achieved by normal fuel sequencing.

5.7.2 Response-Type Verification The time responses of all fourteen configurations were verified during the first evaluation flight. Step responses of several parameters such as q, α, and n_{z_p} were recorded and compared to the Calspan off line simulator step responses. The results, shown in Appendix E, compared favorably, verifying the desired response-types were evaluated during the experiment.

5.7.3 Blind Evaluations The evaluations were conducted with the evaluation pilots unaware of the configuration being evaluated (blind evaluation). Each configuration was programmed with three different experiment numbers so as to keep the pilot blind to the actual configuration being evaluated.

The order in which configurations were evaluated was determined by the project FTE and navigator and usually reflected a desire to observe differences between consecutive evaluations. This was achieved through either a significant change in bandwidth and/or a change in response-type from one evaluation to the next.

Each sortie began with three practice hookups using configuration C1. This was done intentionally (with the pilot aware of the configuration) to reset a baseline. Following the warm-up, as many blind evaluations as fuel permitted were accomplished. Configuration C1 was also flown during the blind evaluations to collect unbiased data for this conventional response-type.

For each blind evaluation, a minimum of three engagements were accomplished with a configuration before specifically referring to the pilot comment card and assigning ratings. Pilot commentary was encouraged at any time during an evaluation. Immediately after the last disconnect for a configuration, the evaluation pilot transferred control to the Calspan safety pilot and addressed the items on the pilot comment card. On each pilot's last evaluation sortie, additional commentary was gathered (*after* accomplishing the task and rating the configuration) by attempting to position the probe tip at the top, bottom, and center of the drogue at close range (one to two feet) with little to no closure.

Intra- and interpilot variability were minimized throughout the experiment by a combination of experiment design and test team discipline. Intrapilot variability was minimized by allowing the pilots adequate time (hookups) to get comfortable with each configuration prior to assigning ratings. Pilots provided supporting comments when rating each configuration to ensure decision tree processes were being used. Interpilot variability was minimized by similarity in the order that each configuration was evaluated.

VI. Flight Test Results and Analysis

6.1 Introduction

All fourteen configurations were flight tested in the probe and drogue air refueling task using an S-3A tactical tanker equipped with an air refueling store (ARS). Eight evaluation sorties in NT-33A and eight S-3A support sorties were flown at Patuxent River NAS, Maryland from 9 to 11 October 1993. A total of 58 blind evaluations were accomplished, thirty by Pilot A and twenty-eight by Pilot B.

All flight test objectives were met except for an evaluation of the *desired* ACAH response-types. An improperly mechanized trim system hindered the evaluation of the ACAH configurations. As tested, all the ACAH configurations were unsuitable for probe and drogue air refueling due mainly to the trim system and partly to non-optimum command gains. However, the basic response to the pilot's stick force input was correct and the task could still be accomplished despite the trim system problem.

The probe and drogue air refueling task was easier to accomplish than expected. In fact, desired performance was achieved on *every* evaluation. There were several reasons for this. First, the turbulence level was light for most, if not all, of the evaluations and consequently the drogue was stable. Also, the probe was located in a favorable position well in front of the aircraft and near the roll axis. Consequently, no discernible interaction between the drogue and the airflow over the nose of the aircraft was observed and roll inputs resulted in very little translation of the probe tip.

Although desired performance was achieved on all the evaluations, the workload required to achieve that performance varied noticeably. Compensation techniques varied with the degree predictability of the initial response and with the precision of control available. Better configurations allowed the pilot to cross check the drogue more often and center the probe within the drogue. As precision of control decreased, more time was spent

focusing on the S-3A while viewing the drogue with peripheral vision. Further degradation in the predictability of the initial response required focusing mainly on the S-3A, keeping the drogue in the peripheral vision, lightly gripping the stick, making only small inputs, and increasing the closure rate. Attempts to tightly control the poor handling configurations near the drogue resulted in over control and a missed engagement. Workload after engaging the drogue decreased noticeably for the better configurations and remained high for the oversensitive configurations and the ACAH configurations.

Despite similar backgrounds, the evaluation pilots had different piloting techniques. Pilot A tended to fly a smooth aircraft and accomplish the task as planned. This technique resulted in consistent ratings but did not expose degraded handling qualities for gain margin limited aircraft when exerting tight control. Pilot B tended to use finesse and a slower than planned approach speed on some evaluations. This technique exposed flying qualities deficiencies in the gain margin limited aircraft (reflecting the handling qualities for these aircraft depended on the level of aggressiveness). It also introduced considerable variability in the pilot ratings. Both techniques exposed different problems with some of the configurations. Also, *both* techniques worked satisfactorily with the better configurations.

A range of flying qualities were observed during the experiment. Results of the flight test are presented below beginning with a synopsis of the primary data; the pilot's commentary. The pilot commentary were transcribed from the HUD video tapes and are documented in Appendix F. Pilot ratings are presented next. Both the intra and interpilot variability are discussed. Finally, flight test results are analyzed in terms of the Bandwidth criterion and control sensitivity parameters.

6.2 RCAH Flight Test Results

The specific objective was to qualitatively and quantitatively evaluate the suitability of selected RCAH response-types for probe and drogue air refueling over a range of pitch

attitude bandwidths from approximately 2.0 to 7.0 rad/sec and over a range of flight path bandwidths from approximately 1.0 to 3.0 rad/sec.

6.2.1 Configuration R1 Results Configuration R1 was not suitable for the probe and drogue air refueling task. The aircraft was overly sensitive, PIO prone and did not allow precise control. Tight control resulted in undesirable oscillations and accelerations and often resulted in a missed engagement. The over sensitivity was obvious when first entering the control loop, and persisted throughout all phases of the task. Compensation techniques included focusing almost exclusively on the S-3A, keeping the drogue in the peripheral vision, lightly gripping the stick and making only small inputs, and increasing closure once stable with the S-3A and lined up with the drogue.

6.2.2 Configuration R2 Results Configuration R2 was suitable for the probe and drogue air refueling task. The initial response was predictable and allowed precise control. One evaluation, conducted by Pilot A, showed some problems with precise control near the drogue when turbulence was a factor (turbulence rating C, minor degradation of task performance due to the turbulence). No special compensation techniques were required.

6.2.3 Configuration R3 Results Configuration R3 was acceptable for the probe and drogue air refueling task. Most of the engagements showed some problems with precise control near the drogue in the form of a pitch bobble or wandering flight path. Attempts to look directly at the drogue in close and make fine corrections were difficult. Pilot A also experienced flight path problems further out. The aircraft flight path would tend to drift off slightly. Compensation techniques included using a lighter stick grip, making smooth gentle inputs, and focusing more on the S-3A.

6.2.4 Configuration R4 Results Configuration R4 was acceptable for the probe and drogue air refueling task. Most engagements showed problems with precise control near the drogue. Attempts to exert tight control near the drogue resulted in oscillations for Pilot B. Pilot A also experienced flight path problems further out. The aircraft flight path would tend to drift off slightly. Compensation techniques included focusing more on the S-3A,

keeping the drogue in the peripheral vision, and increasing closure rate once stable with the S-3A and lined up with the drogue. Both pilots compensated for the lack of precise pitch pointing capability by accepting a contact within the drogue rather than a direct contact with the center of the drogue.

6.2.5 Configuration R1X Results Configuration R1X was not suitable for the probe and drogue air refueling task. The aircraft was overly sensitive, PIO prone and did not allow precise control. Tight control resulted in undesirable motions and accelerations that compromised task performance. The over sensitivity was obvious when first entering the control loop, and persisted throughout all phases of the task. Compensation techniques included focusing almost exclusively on the S-3A, keeping the drogue in the peripheral vision, lightly gripping the stick and making only small inputs, and increasing closure once stable with the S-3A and lined up with the drogue.

6.2.6 Configuration R2X Results Configuration R2X was suitable for the probe and drogue air refueling task. Precision of control was good. The aircraft response was predictable enough to look at the drogue more often and exert tight control in close. Stick forces were satisfactory and no special compensation techniques were required to achieve desired performance.

6.2.7 Configuration R3X Results Configuration R3X was suitable for the probe and drogue air refueling task. Precision of control was good. On two out of three evaluations, Pilot B commented configuration R3X was one of the best configurations flown. However, on the other evaluation, Pilot B gave configuration R3X a Cooper-Harper handling qualities rating of 5 (and also admitted he was tired on this ninth blind evaluation of the sortie). Pilot B felt the handling qualities of configuration R3X degraded under tight control. Stick forces were satisfactory, the initial response was predictable, and no special compensation techniques were required to achieve desired performance.

6.2.8 Configuration R4X Results Configuration R4X was acceptable for the probe and drogue air refueling task. Most engagements showed problems with precise control near

the drogue. Attempts to exert tight control near the drogue resulted in pitch bobbles. Stick forces were slightly light. Compensation techniques included focusing more on the S-3A, keeping the drogue in the peripheral vision, and increasing closure rate once stable with the S-3A and lined up with the drogue. Both pilots compensated for the lack of precise pitch pointing capability by accepting a contact within the drogue rather than a direct contact with the center of the drogue.

6.2.9 Analysis of RCAH Results The RCAH specific objective was met. Six of the eight RCAH configurations (R2, R3, R4, R2X, R3X, and R4X) were suitable for the probe and drogue air refueling task. The other two configurations (R1 and R1X) were unsuitable for the task.

The best RCAH configurations were configurations R2, R2X, and R3X. Both pilots evaluated configurations R2 and R2X once and configuration R3X three times. These configurations had predictable initial responses, satisfactory stick forces, and required no special compensation techniques to achieve desired performance. Stick force per g for configurations R2, R2X, and R3X were approximately 4 lb/g, 5 lb/g, and 7 lb/g respectively (a nominal $F_{es}/n \cong 6$ lb/g). These values were essentially within the range desired during the 1974 experiment. The best RCAH configurations from this experiment also had the same basic combination of bandwidths ($\omega_{BW_\theta}/\omega_{BW_\gamma} \cong 2.9$) as the Level 1 aircraft from the 1974 experiment.

In general, the RCAH configurations with an extended bandwidth prefilter (configurations R1X through R4X) allowed slightly finer control near the drogue than the RCAH configurations without a prefilter (configurations R1 through R4). Success rates, pilot comments, Cooper-Harper ratings, and PIO ratings were all slightly better for the extended bandwidth configurations. The primary effect of the prefilter was the addition of lead compensation that increased both the pitch attitude and flight path bandwidths.

The higher bandwidth, slightly gain margin limited, RCAH configurations (R4 and R4X) were acceptable for the task. Attempts to exert tight control with these configurations

resulted in oscillations and pitch bobbles, respectively. Both pilots compensated for the lack of precise control by accepting a contact within the drogue rather than a direct contact with the center of the drogue.

The lower bandwidth configurations (R1 and R1X) had high command gains which made them overly pitch sensitive, and PIO prone. The control sensitivity problems could be predicted using $|\theta/F_{es}|_{\omega_{BW_\theta}}$, $|\gamma/F_{es}|_{\omega_{BW_\gamma}}$, or F_{es}/n and were a consequence of fixing $\dot{q}/F_{es}$ at approximately 5.5 $\text{deg}/\text{lb}-\text{sec}^2$. The PIO ratings and inflight comments for these two configurations agree with Roger Hoh's observation that excessively high control sensitivity looks like low damping, is therefore PIO prone, and will receive comments to that effect [Hoh88, p.7]. Whether these two configurations would be suitable with optimum command gains is undetermined.

Different flying techniques exposed different problems with some of the RCAH configurations. Tight control exposed pitch bobbling problems with the high bandwidth, gain margin limited RCAH configurations (R4 and R4X) and smooth control exposed longer term flight path problems for other high bandwidth RCAH configurations (R3 and R4). While both problems are undesirable, the pitch bobbling tendency is usually of greater concern, and reemphasizes the need to fly tight exacting tasks (such as HQDT) to expose handling qualities deficiencies.

6.3 ACAH Flight Test Results

The specific objective was to qualitatively and quantitatively evaluate the suitability of selected ACAH response-types for probe and drogue air refueling over a range of pitch attitude bandwidths from approximately 3.0 to 7.0 rad/sec and over a range of flight path bandwidths from approximately 1.5 to 3.5 rad/sec.

6.3.1 Configuration A1 Results Configuration A1 was not suitable for the probe and drogue air refueling task. The aircraft was overly sensitive and had very undesirable

bucking motions and accelerations for small stick force inputs. Fine control was difficult. The over sensitivity was obvious when first entering the control loop, and persisted throughout all phases of the task. The aircraft also had objectionable trim system problems. Compensation techniques were to lightly grip the stick and make only small inputs.

6.3.2 Configuration A2 Results Configuration A2 was not suitable for the probe and drogue air refueling task. The aircraft was somewhat sensitive and had undesirable accelerations for small stick force inputs. Tight control near the drogue resulted in pitch bobbles. The undesirable motions were not as bad as those encountered with configuration A1, but were still noticeable. The aircraft also had very objectionable trim system problems (worse than configuration A1). Compensation techniques were to lightly grip the stick and make only small inputs.

6.3.3 Configuration A3 Results Configuration A3 was not suitable for the probe and drogue air refueling task. The trim system did not allow either evaluation pilot to trim the aircraft satisfactorily and noticeable attention was required to keep the stick forces manageable. There was a slight feeling of quickness in the initial aircraft response. However, the aircraft could be precisely pointed. Pilot A felt this precision gave a feeling of being able to control the flight path directly. Additionally, the predictability of the response allowed the drogue to viewed directly during all approaches. Compensation techniques were primarily keeping the stick forces manageable.

6.3.4 Configuration A4 Results Configuration A4 was not suitable for the probe and drogue air refueling task. The trim system did not allow either evaluation pilot to trim the aircraft satisfactorily and considerable attention was required just to keep the stick forces manageable. More than once, the stick forces became excessive and several off axis disconnects occurred when the drogue was not returned to the trail position. Occasionally, Pilot B reached a stick stop and fell off the drogue. When the stick forces were light, the aircraft could be precisely pointed. Again, Pilot A felt this precision gave a feeling of being able to control the flight path directly. Pilot B, however, felt the precision of control came at

the expense of responsiveness and consequently felt the aircraft was sluggish. The predictability of the response allowed the drogue to viewed directly during all approaches. Compensation techniques were primarily keeping the stick forces manageable.

6.3.5 Analysis of ACAH Results The ACAH specific objective was not met. The response of the ACAH configurations to the pilot's stick force input was correct (as verified by the step inputs). However, the response to the pilot's trim input was completely wrong. The *desired* response-type was not being evaluated any time the evaluation pilot used a combination of both stick force and trim inputs. Trim inputs were necessary to various degrees on every evaluation.

Both evaluation pilots immediately recognized the ACAH trim system was unsatisfactory, but neither pilot identified the reason. The importance of pilot commentary was clearly demonstrated during the ACAH evaluations. During one particular evaluation, Pilot A gave a running commentary of both the stick force required to hold level flight and the trim input used to relieve that stick force. The trim input was opposite the direction of stick force (opposite the direction of normal trim operation). During other evaluations, Pilot B ran the trim in an effort to relieve heavy stick forces only to observe the aircraft continue pitching at an ever increasing rate in the opposite direction of the applied trim. More than once Pilot B was against a stick stop and had to abandon the task.

Ultimately, both pilot's did whatever it took to accomplish the task. Without realizing exactly how they were doing it, both pilot's were usually able to adapt to the faulty trim system. Neither pilot was able to trim the aircraft for any length of time and both actively used the trim system (described by both pilot's as a cycling trim). Pilot A usually attempted to trim the aircraft in precontact and engage the drogue without further use of the trim system. Pilot B used the trim considerably more. After engaging the drogue, the workload decreased greatly and often both pilot's reverted to the usual trim techniques, which of course made the problem worse. Often excessive stick forces were being held during

disconnects which made it difficult to return the drogue to the trail position. Consequently, several off axis disconnects occurred with the ACAH configurations.

The cause of the trim system problem was identified after the evaluation flights. During the initial calibration flights, the trim system was correctly implemented; both the pilot's stick force and trim input commanded pitch attitude (the trim system input was summed with the pilot's stick force input ahead of the washout prefilter). However, the calibration pilot felt the requested frequency sweeps were impossible to accomplish and the trim was not working as desired because the trim inputs were "washed out". Additionally, since turn compensation wasn't incorporated in the ACAH configurations, excessive aft stick forces (which couldn't be completely trimmed out) were required during turns. The trim system input was then moved downstream of the washout prefilter for the evaluation flights. The problem with this implementation was a trim input now commanded pitch rate rather than pitch attitude. To make matters worse, the trim input caused an ever increasing pitch attitude in the opposite direction of that intended (due to a sign change in the command path between the old and new summing locations)[1].

To both evaluation pilots, the trim problem was noticeably worse for configuration A4 and decreased in severity for configurations A3, A2, and A1. This was due to the command gains used. Configuration A4 had the lowest command gain (the least pitch attitude authority) and hence required the most stick force to counteract the runaway trim.

The command gains used for the ACAH configurations were not optimum for the task. Attempting to hold $\dot{q}/F_{es}$ constant among the configurations resulted in very different pitch

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[1]Calspan block diagrams for the ACAH configurations depict the command gain negated and the command path summed with the feedback return, whereas the HAVE GAS block diagram in Figure E.2 depicts a positive command gain and the command path differenced with the feedback return.

sensitivities for the four configurations. Pitch sensitivity ranged from overly sensitive (configuration A1) to sluggish (configuration A4).

In general, the pitch acceleration divided by stick force, $\dot{q}/F_{es}$, is a function of command gain, frequency (bandwidth), damping, and the prefilter. The ACAH configurations all used the same effective damping ratio, $\zeta' = 0.7$, so $\dot{q}/F_{es}$ was not a function of damping ratio. If the command gain is held constant among the ACAH configurations, the combined effects of increasing ω' and the washout prefilter are to increase $\dot{q}/F_{es}$. However, since $\dot{q}/F_{es}$ was held approximately constant, the command gain was adjusted as a function of bandwidth. The lowest bandwidth configuration (A1) had a very high command gain and the highest bandwidth configuration (A4) had a very low command gain.

Configuration A1, was overly pitch sensitive, PIO prone, and did not allow precise control. Configuration A2 had similar characteristics, but not to the extent of configuration A1. These configurations exhibited a unique and undesirable pitch acceleration described by both pilots as a "bucking motion" or "quickness". Both up and down accelerations were experienced for a single stick force input. This characteristic was barely perceptible and not observed in the higher bandwidth ACAH configurations (A3 and A4 respectively). Configurations A3 and A4 exhibited precise pitch pointing characteristics. Pilot A felt this was highly desirable and that it gave a feeling of being able to control the flight path directly. However, Pilot B felt the pitch pointing precision came at the expense of responsiveness (the aircraft was now sluggish). Any future evaluation of ACAH should concentrate on optimizing the command gain for the task and determining the suitability of the response to a variety of piloting techniques. Nonlinear stick shaping may be required to resolve the conflicting requirements of avoiding undesirable accelerations for small stick inputs while still maintaining adequate pitch authority when required.

The pitch accelerations encountered with the ACAH response-types were unique in terms of the degree of both up and down accelerations experienced. Figure 6.1 depicts a

comparison of the pitch rate time responses for configurations R3, R3X, and A3 to a 10 lb boxcar input.

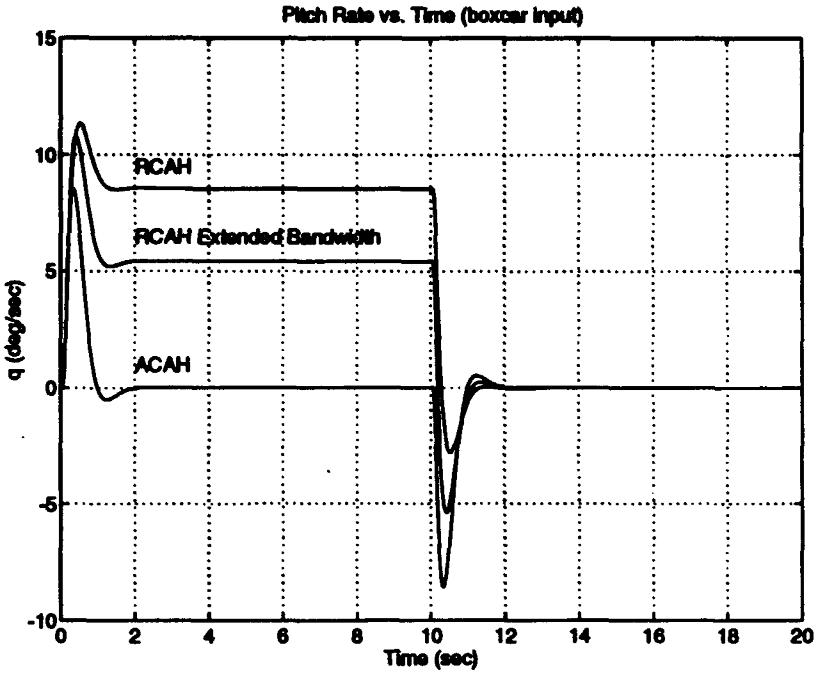

Figure 6.1. Comparison of Pitch Rate Time Responses

The initial slopes of q for the three configurations are similar, reflecting $\dot{q}/F_{es}$ was closely matched. However, the degree of pitch rate overshoot is very different for the three configurations. The ACAH response-type has considerably more overshoot. For the ACAH response-type, the difference between q_{peak} and q_{ss} is greater and the ratio q_{peak}/q_{ss} is infinite. This degree of overshoot probably represents close to the maximum allowable without being objectionable (the initial response for configuration A3 was described as having a slight quickness). For the lower bandwidth ACAH configurations (A1 and A2), the command gains were higher resulting in excessive pitch rate overshoot and the accelerations were objectionable.

The STI Dropback criterion predicts excessive dropback as the response-type approaches ACAH with no regard for the influence of the command gain on either the

magnitude of the pitch rate response or the pitch acceleration(s). A good abruptness metric (control sensitivity metric) for precision tracking tasks needs to account for the influence of the command gain and emphasize the characteristics of the mid-frequency response.

6.4 High Dropback Conventional Response-Type Flight Test Results

The specific objective was to qualitatively and quantitatively evaluate the suitability of configuration C1X for the probe and drogue air refueling task. Configuration C1X replicates configuration 2A from the 1974 Calspan experiment. Configuration 2A was analyzed as a high dropback case and was rated Level 1 with pilot comments indicating pitch bobbling (evaluated only once).

6.4.1 Configuration C1X Results Configuration C1X was not suitable for the probe and drogue air refueling task due to objectionable pitch sensitivity. The initial response was too abrupt and did not allow precise pitch pointing capability. The aircraft had abrupt pitch accelerations for small stick force inputs. The over sensitivity was obvious when first entering the control loop, and persisted throughout all phases of the task. Fine pitch control near the drogue was impossible. Attempts to exert tight control near the drogue resulted in undesirable pitch motions and task performance was compromised. Compensation techniques included focusing mainly on the S-3A while viewing the drogue in the peripheral vision, lightly gripping the stick, making very small stick inputs, and increasing the closure rate once aligned with the drogue. Both pilots compensated for the lack of precise pitch pointing capability by accepting a contact within the drogue rather than a direct contact with the center of the drogue.

6.4.2 Analysis of Configuration C1X Results The specific objective was met. The poor handling were predicted by not only the STI Dropback criterion (using the short period approximation analysis in Chapter 3), but by $|\theta/F_{es}|_{\omega_{BW_\theta}}$ and $|\gamma/F_{es}|_{\omega_{BW_\gamma}}$ and were verified inflight.

6.5 *Comparison of Response-Types Flight Test Results*

The specific objective was to qualitatively and quantitatively compare the suitability of the best RCAH and ACAH configurations found during flight test with configuration C1. Configuration C1 replicates configuration 2D, one of the best conventional response-types from the 1974 Calspan experiment.

6.5.1 Configuration C1 Results Configuration C1 was suitable for the probe and drogue air refueling task. The initial response was satisfactory and the aircraft had satisfactory pitch pointing capability. Both pilot's commented the stick forces were lighter than they would have preferred (a comment also made by Pilot A from the 1974 Calspan experiment). Compensation techniques were lightly gripping the stick and making small stick force inputs.

6.5.2 Response-Type Comparison Results The specific objective was only partially met. The ACAH configurations were not included in this comparison because the improperly mechanized trim system did not allow an objective comparison. Had the trim system worked properly, the results probably would have been very interesting. Because the evaluations were blind, the preferences were determined after all the evaluations were complete.

The best RCAH and conventional response-types from this experiment were all suitable for the task with no clear advantage for one over the other. Excluding the ACAH configurations from consideration, both pilots agreed the best configurations were R2, R2X, R3X, and C1. These configurations all had the same basic combination of bandwidths ($\omega_{BW_\theta}/\omega_{BW_\gamma} \cong 2.9$) and control sensitivities (a nominal $F_{es}/n \cong 6$ lb/g). The differences between these configurations were minor and choosing a best configuration was really a matter of personal preference. Both pilot's preferred a RCAH configuration over the conventional response-type. Pilot A preferred configuration R3X and Pilot B preferred configuration R2.

Pilot A considered configuration R3X to be the best RCAH configuration. Although Pilot A felt the differences between R3X and C1 were subtle, configuration R3X was preferred.

On two out of three evaluations, Pilot B commented configuration R3X was one of the best configurations flown. However, on the other evaluation, Pilot B gave configuration R3X a Cooper-Harper handling qualities rating of 5 (and also admitted he was tired on this ninth blind evaluation of the sortie). Pilot B felt the handling qualities of both configurations R3X and C1 degraded slightly under tight control and consequently selected configuration R2 as best configuration for its finer predictability and ability to precisely position the probe (based on only one evaluation of configuration R2).

The similarities and differences between the response-types can be seen clearly by comparing the θ/F_{es} and γ/F_{es} frequency responses. Figure 6.2 is a comparison of the θ/F_{es} frequency responses for configurations R3, R3X, and A3.

The RCAH has a greater magnitude at lower frequencies and lesser magnitude at higher frequencies. It's phase margin is less than either RCAH extended bandwidth or ACAH and so RCAH has a low bandwidth by comparison. RCAH extended bandwidth and ACAH magnitudes differ at lower frequencies and are essentially identical at higher frequencies. The ACAH has greater phase margin and hence a higher bandwidth.

Figure 6.3 is a comparison of the γ/F_{es} frequency responses for configurations R3, R3X, and A3. The same trends hold for the γ/F_{es} frequency responses as the θ/F_{es} frequency responses.

For clarity, configuration C1 was left out of Figures 6.2 and 6.3. However, over the frequency range from 0.1 to 10 rad/sec, the frequency responses for configuration C1 were nearly identical to those of configuration R3X. Configuration C1 had slightly higher magnitude in the crossover region. This factor alone could probably explain why both pilots preferred a RCAH configuration over configuration C1.

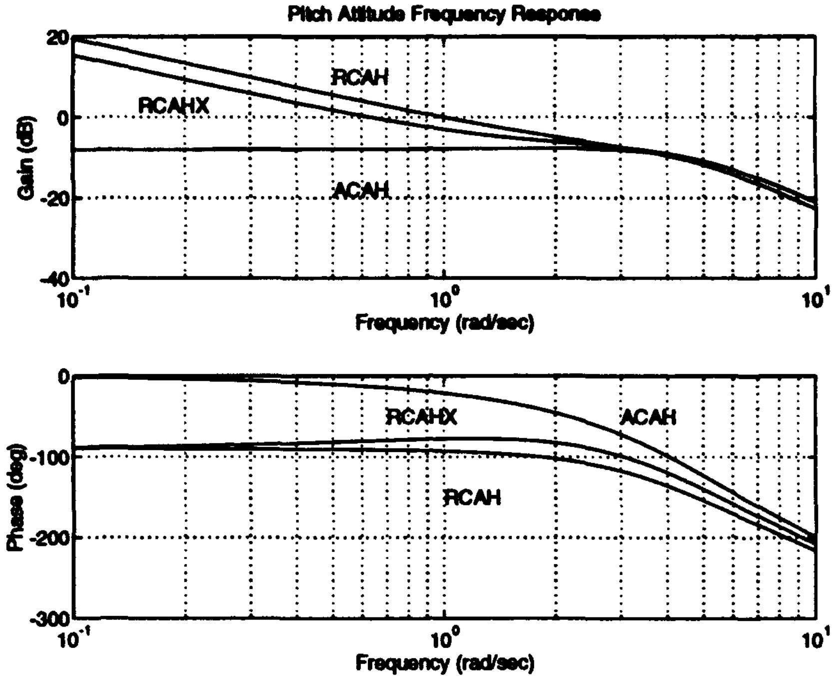

Figure 6.2. Comparison of θ/F_{es} Frequency Responses[2]

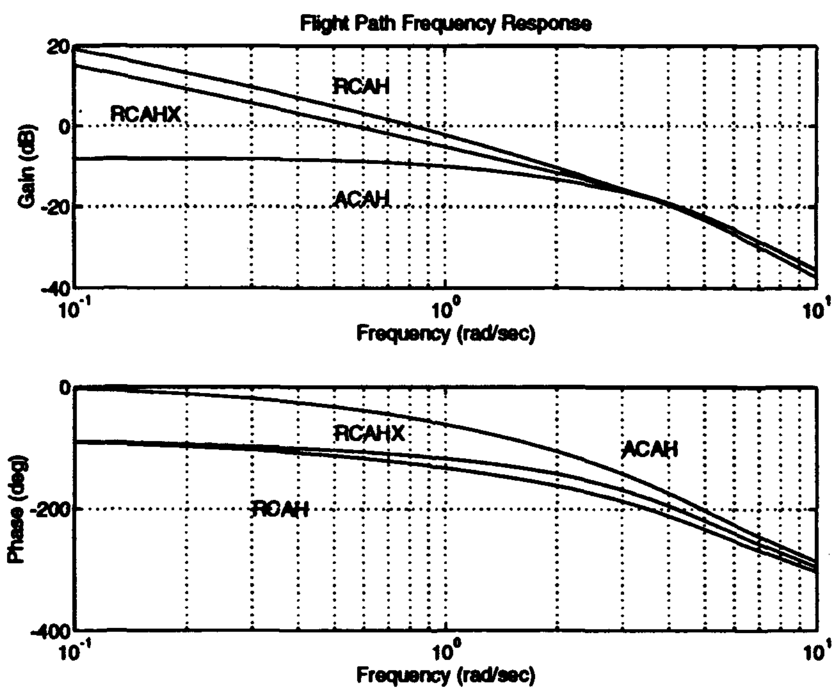

Figure 6.3. Comparison of γ/F_{es} Frequency Responses[2]

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[2]RCAHX is RCAH extended bandwidth.

6.6 Handling Qualities Ratings

6.6.1 Cooper-Harper Handling Qualities Ratings Flying qualities experiments rely on Cooper-Harper handling qualities ratings as well as pilot comments to determine desirable aircraft dynamics. Pilot Ratings for the HAVE GAS configurations are summarized in Table 6.1 and Table 6.2.

Significant variability exists in some of the handling qualities ratings and to a lesser extent in some of the PIO ratings. Cooper-Harper rating variability reduces an engineers' confidence in the results. However, the sources for most of the rating variability in this experiment were identified during or shortly after the evaluations. Rating variability for gain margin limited configurations were expected (ratings depend on the level of aggressiveness used). The rating variability that resulted from the improperly mechanized ACAH trim system was inevitable given the severity of the problem and the time constraints of the project.

The inability to satisfactorily trim the ACAH configurations caused considerable variability in the pilot ratings (both handling qualities and PIO) for these configurations. Both pilots quickly realized their was a serious problem with the trim system. Pilot A *attempted* to ignore the workload associated with trim system and assess (project) the suitability of the basic response to his stick force inputs. Pilot B rated the suitability of the configurations as a whole. Additionally, Pilot B included the low frequency oscillations associated with chasing the trim in his PIO ratings. When assigning PIO ratings, Pilot A only included any high frequency oscillations that occurred while performing the task. This different use of the PIO rating scale is evident in the PIO ratings assigned for configurations A3 and A4. Only after the evaluation, was the different use of the PIO tendency rating scale realized.

Table 6.1. Summary of Pilot Ratings for RCAH Response-Type Configurations

Summary of Pilot Ratings for RCAH Response-Type Configurations																					
Config	Pilot	Flight Number				Hookups/Attempts				Cooper-Harper Rating				PIO Rating				Turbulence Rating			
		Eval 1	Eval 2	Eval 3	Eval 4	Eval 1	Eval 2	Eval 3	Eval 4	Eval 1	Eval 2	Eval 3	Eval 4	Eval 1	Eval 2	Eval 3	Eval 4	Eval 1	Eval 2	Eval 3	Eval 4
R1	A	2	6	8		3/6	3/4	3/5		6	7	7		4	4	4		A	B	C	
	B	1	5	7		3/4	3/3	3/6		5	5	7		4	4	4		B	A	B	
R2	A	4				3/6				1				1				C			
	B	3				3/3				1				1				A			
R3	A	2	6			3/3	3/4			2	2			1	1			A	B		
	B	1				3/3				3				2				B			
R4	A	4	6	8		3/3	3/3	3/3		2	2	2.5		1	1	1		B	B	B	
	B	3	5	7		3/4	3/5	3/3		5	5	1		4	4	1		A	B	B	
R1X	A	4				3/4				5				3				A			
	B	3				3/3				4				3				A			
R2X	A	2				4/4				1				1				A			
	B	3				4/4				2				1				B			
R3X	A	2	6	8		3/3	3/3	3/3		1	2	2		1	1	1		A	B	C	
	B	1	5	7		3/3	3/4	3/3		1	5	2		1	1	1		B	A	C	
R4X	A	4				3/3				2				1				B			
	B	5				3/3				3				2				A			

Table 6.2. Summary of Pilot Ratings for ACAH and Conventional Response-Type Configurations[3]

Summary of Pilot Ratings for ACAH and Conventional Response-Type Configurations																					
Config	Pilot	Flight Number				Hookups/Attempts				Cooper-Harper Rating				PIO Rating				Turbulence Rating			
		Eval 1	Eval 2	Eval 3	Eval 4	Eval 1	Eval 2	Eval 3	Eval 4	Eval 1	Eval 2	Eval 3	Eval 4	Eval 1	Eval 2	Eval 3	Eval 4	Eval 1	Eval 2	Eval 3	Eval 4
A1	A	4	6	8		3/3	3/3	3/3		(6)	(6)	7(6)		2	3	3		A	B	A	
	B	3	7			3/3	3/4			5	6(5)			4	4			A	B		
A2	A	2	6			3/3	3/4			(4)	(5)			2	2			A	B		
	B	1	5			3/3	3/3			5	5			4	4			B	A		
A3	A	4	6	8		3/3	3/3	3/4		(2)	(1)	7(2)		1	1	1		B	B	B	
	B	3	5	7		3/3	3/3	3/3		5	(3)	5(3)		3	2	2		A	A	A	
A4	A	2	4	6	8	3/3	3/3	3/4	3/3	(2)	(1)	(2)	8(1)	1	1	1	1	A	B	B	B
	B	3	5	5	7	3/4	3/4	3/3	3/4	6	5	9(3)	7(5)	3	3	1	3	A	A	A	A
C1	A	4	6			3/3	3/3			2	1			1	1			B	B		
	B	3	5			3/3	3/3			3	2			2	1			A	A		
C1X	A	4				3/3				6				3				B			
	B	5				3/3				5				2				A			

[3]Cooper-Harper Ratings in parethensis are projected ratings (workload associated with faulty trim system is ignored).

Time constraints did not permit stopping the evaluation flights to identify and fix the trim system problem. Instead, once the FTE and navigator realized the evaluation pilots were rating different things, they had each pilot rate the ACAH configurations both ways on their last evaluation flight. To what extent the projected handling qualities ratings are valid is questionable given the high workload associated with the faulty trim system and the hybrid nature of the actual aircraft response (influenced by both the stick force and trim inputs). Justifiably, Pilot B could not ignore the trim problems in any of his ratings and consequently his ratings reflect the severity of the trim system deficiencies more than Pilot A's ratings. Both Pilot A's projected ratings and Pilot B's whole system ratings were similar for configurations A1 and A2 reflecting the major problem with these configurations was control sensitivity. The ratings really began to differ with configurations A3 and A4 where the trim system problems were very objectionable, but the response was desirable and each pilot rated different things.

6.6.2 Intrapilot Variability Intrapilot variability occurs when a single pilot cannot reliably repeat his evaluations of a configuration. The biggest source of intrapilot variability in this experiment was the level of aggressiveness used by Pilot B during evaluation flights three and five. From a pure numbers point of view, the variability looks bad. However, the degradation in handling qualities experienced with the gain margin limited configurations as the of level aggressiveness (tight control) increased was expected and is *valuable* information. Pilot A's level of aggressive did not expose these problems as graphically as Pilot B's did.

Plots of intrapilot variability for Pilots A and B are shown in Figures 6.4 and 6.5 respectively. Figures 6.4 and 6.5 are symmetrical about a line of zero HQR variability. Each HQR obtained for a given configuration was plotted once as the independent variable with the other HQRs in the repeated set plotted as the dependent variables.

For example, Pilot A rated configuration R1 three times as 6, 7, and 7. HQR = 6 was taken as the first independent variable and the points (6,7) and (6,7) were plotted on Figure

6.4. The second and third independent variables, HQR = 7, resulted in points (7,6) and (7,7) twice on Figure 6.4. Because these points were coincident, the number "2" was placed in parenthesis at their locations to indicate multiple points. Using this procedure, intrapilot variability on Figures 6.4 and 6.5 appear as deviations from a line of zero variability (perfect agreement), and no single HQR was weighted more heavily than another.

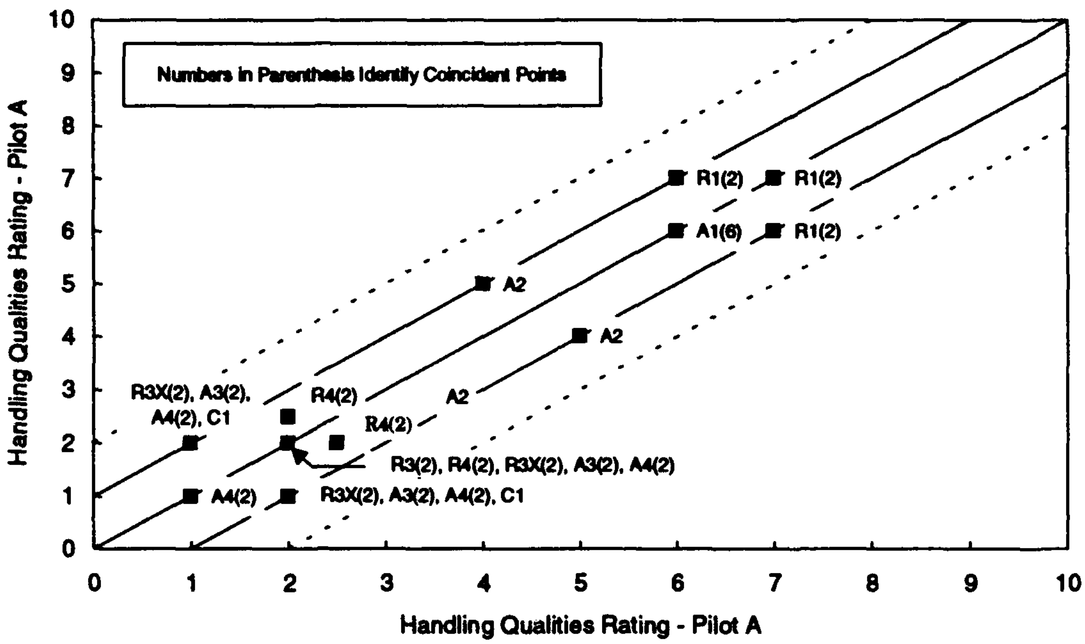

Figure 6.4. Intrapilot Variability, Pilot A

Pilot A was consistent with the use of the Cooper-Harper rating scale (note the ACAH HQRs are the projected ratings where the workload associated with faulty trim system was ignored). One hundred percent of Pilot A's Cooper-Harper handling qualities ratings are within $\Delta HQR \leq 1$. While Pilot A's evaluations and ratings are consistent, they must be used with caution as they don't expose handling qualities deficiencies encountered when exerting tight control. Additionally, most of ratings for the ACAH response-types are projected ratings.

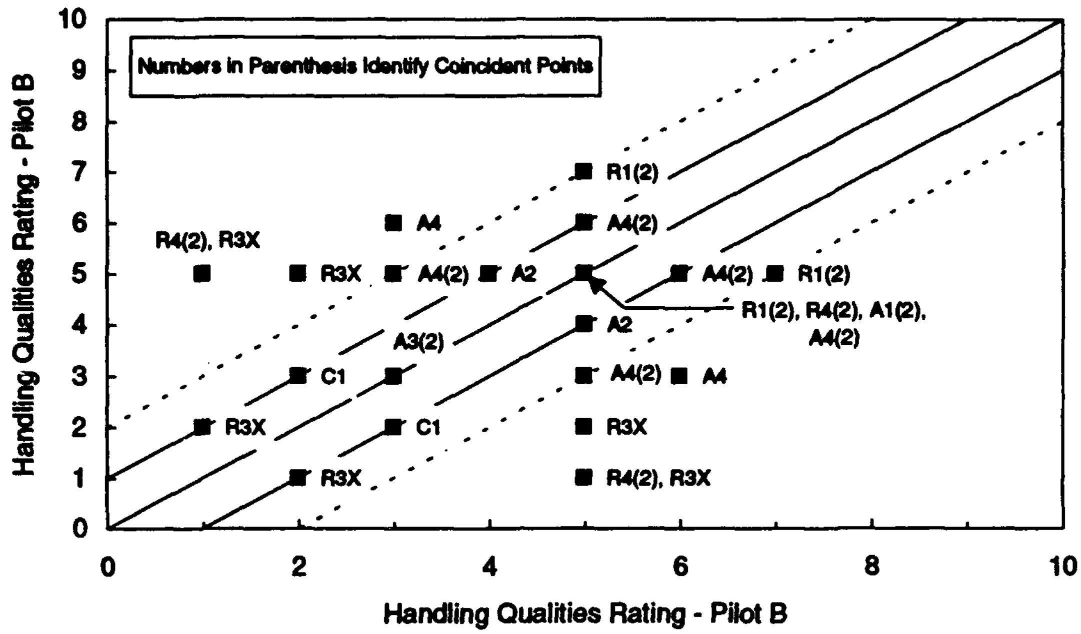

Figure 6.5. Intrapilot Variability, Pilot B

Significant variability exists in Pilot B's handling qualities ratings (note the ACAH HQRs are the ratings for the configuration as a whole). Fifty-three percent of Pilot B's Cooper-Harper handling qualities ratings are within $\Delta HQR \leq 1$ and seventy-four percent are within $\Delta HQR \leq 2$. Configurations with $\Delta HQR \geq 2$ are R4, R3X, and A4. Two of these configurations were gain margin limited and the other was the ACAH configuration with the worst trim system problems. The primary reason for most of Pilot B's intrapilot variability was determined during evaluation flight debriefings. Once Pilot B became comfortable with the probe and drogue air refueling task, he changed the task somewhat. In an effort to distinguish handling qualities differences between some of the configurations, Pilot B slowed his approach to the drogue and aggressively tried to engage the exact center of the drogue. In essence, the task began to resemble an HQDT task versus an operational handling qualities task. Both tasks provide valuable information but yielded significantly different Cooper-Harper handling qualities ratings.

6.6.3 Interpilot Variability Interpilot variability exists because of the natural differences between various pilots and their perceived workloads for a given task. Pilots with similar training, experience in similar aircraft, and the same amount of flight time will not necessarily have the same performance or perceived workload for a given set of aircraft dynamics during a specific task. Other sources of variability include task definition and use of the rating scales. Interpilot variability is determined by plotting the HQRs assigned by one evaluation pilot against the HQRs assigned by another evaluation pilot.

Interpilot variability is shown in Figure 6.6 (note the ACAH HQRs are the ratings assigned on each evaluation pilot's last flight and are the ratings for the configuration as a whole).

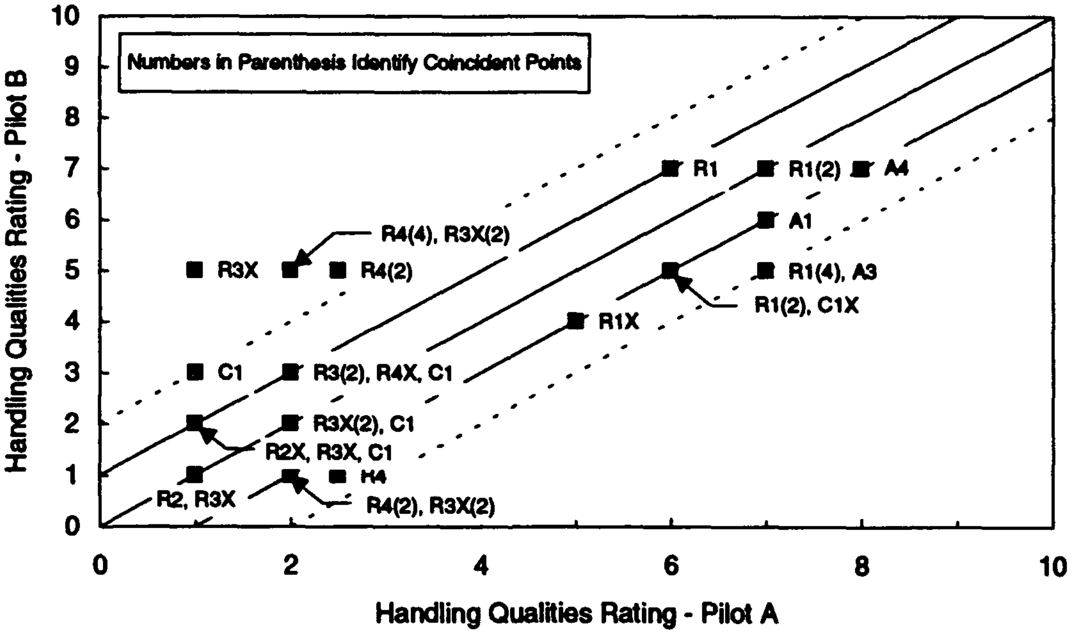

Figure 6.6. Interpilot Variability

Sixty-one percent of the handling qualities ratings are within $\Delta HQR \leq 1$ and seventy-eight percent are within $\Delta HQR \leq 2$. Configurations with $\Delta HQR \geq 2$ are R4 and R3X. Both of these configurations were gain margin limited. The variability in the ratings for these two configurations is primarily due to the different tasks being evaluated (HQDT like vs.

operational task) and the degradation in handling qualities that occurs when exerting tight control with a gain margin limited aircraft.

6.7 *Bandwidth Criterion and Control Sensitivity Analysis*

The Bandwidth criterion parameters are depicted in Figures 6.7 and 6.8 along with the handling qualities ratings for the HAVE GAS configurations.

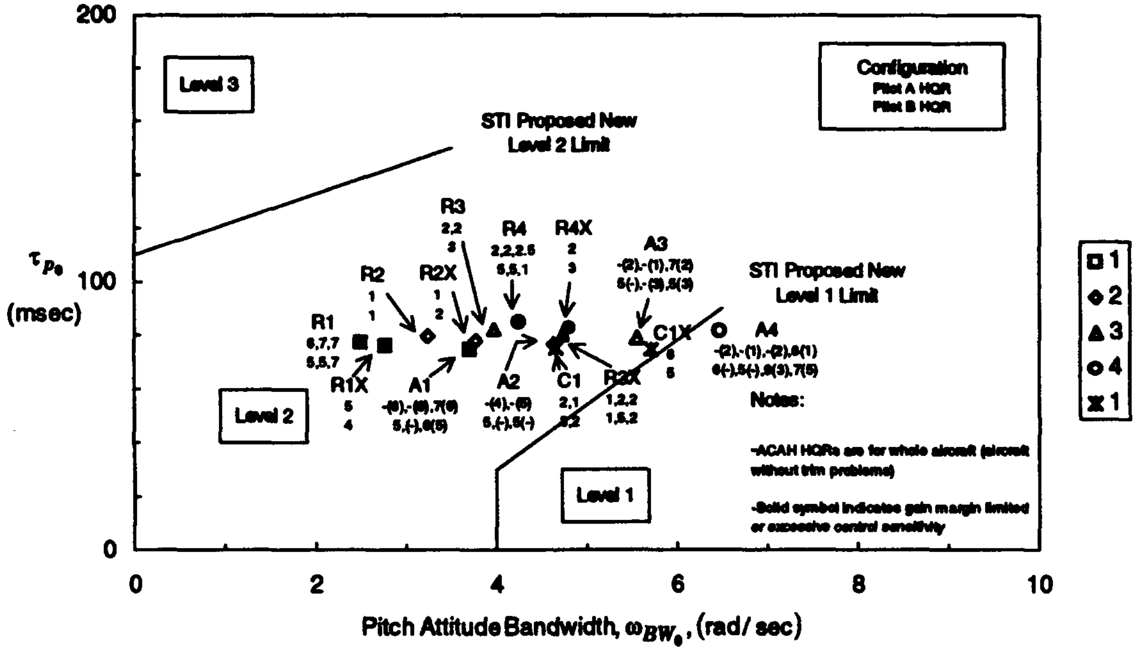

Figure 6.7. Bandwidth Criterion Analysis of HAVE GAS Experiment

Phase delay for the HAVE GAS configurations is nearly double the initial design studies conducted in Chapter 4. This was due to the addition of filters in the command path. Phase delays in this experiment were not excessive, however, every effort should be made to minimize phase delay.

Several configurations plot in the Level 2 region and were rated suitable (Level 1) for the task. It must be emphasized that the HAVE GAS flight test was conducted in nearly ideal conditions (day, VMC, wings level, little turbulence). Before adjusting any boundaries, off nominal conditions require looking at.

The increased pitch and flight path bandwidths for the RCAH extended bandwidth and ACAH configurations are clearly seen in Figure 6.8.

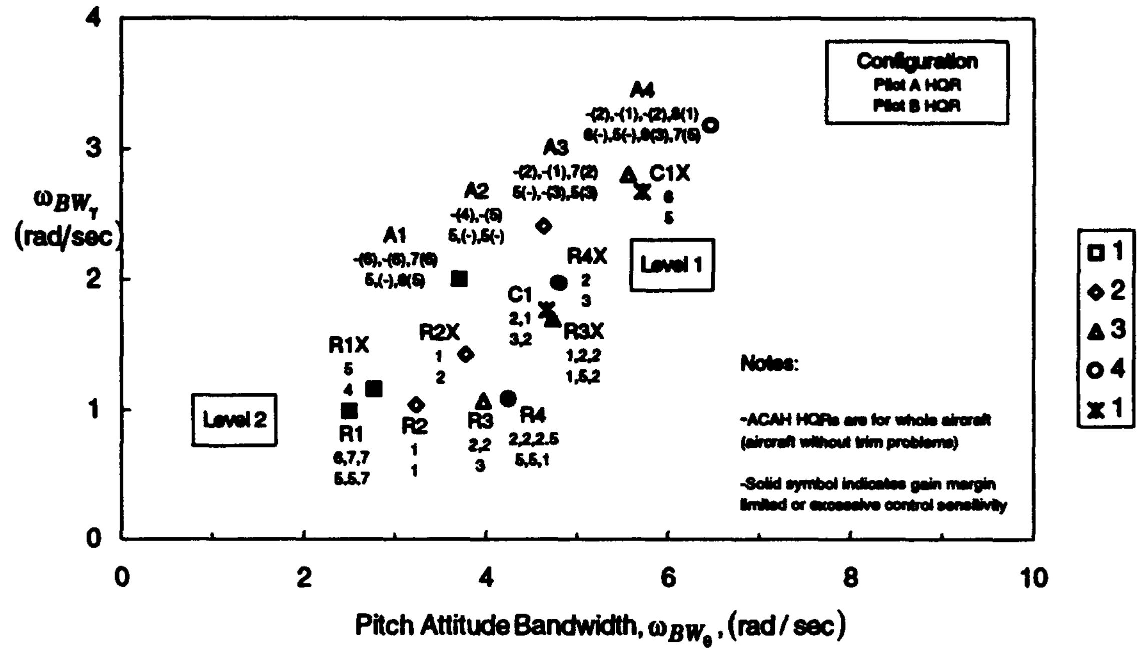

Figure 6.8. Pitch Attitude and Flight Path Bandwidths for HAVE GAS Experiment

More data are required to be able to draw accurate boundaries defining regions of Level 1, 2, and 3 for the Bandwidth plots of Figures 6.7 and 6.8. A complicating issue is how to deal with configurations that had non optimum command gains (control sensitivity). Data from the HAVE GAS experiment show these aircraft can be identified using crossplots of $|\theta/F_{es}|_{\omega_{BW_\theta}}$ vs. ω_{BW_θ} and $|\gamma/F_{es}|_{\omega_{BW_\gamma}}$ vs. ω_{BW_γ}. Control sensitivity trends are shown in Figures 6.9 and 6.10 using data from both the Calspan and HAVE GAS experiments. Overly control sensitive aircraft are separated from the other aircraft and are easily identified (above the lines drawn). Sluggish aircraft also tend to stand out to the left. Figure 6.10 is particularly interesting. The best aircraft fall on a diagonal line with a transition from RCAH response-types at one end, to RCAH extended bandwidth and conventional response-types in the middle, to ACAH response-types at the other end. Requirements for acceptable flight path control sensitivity are tight.

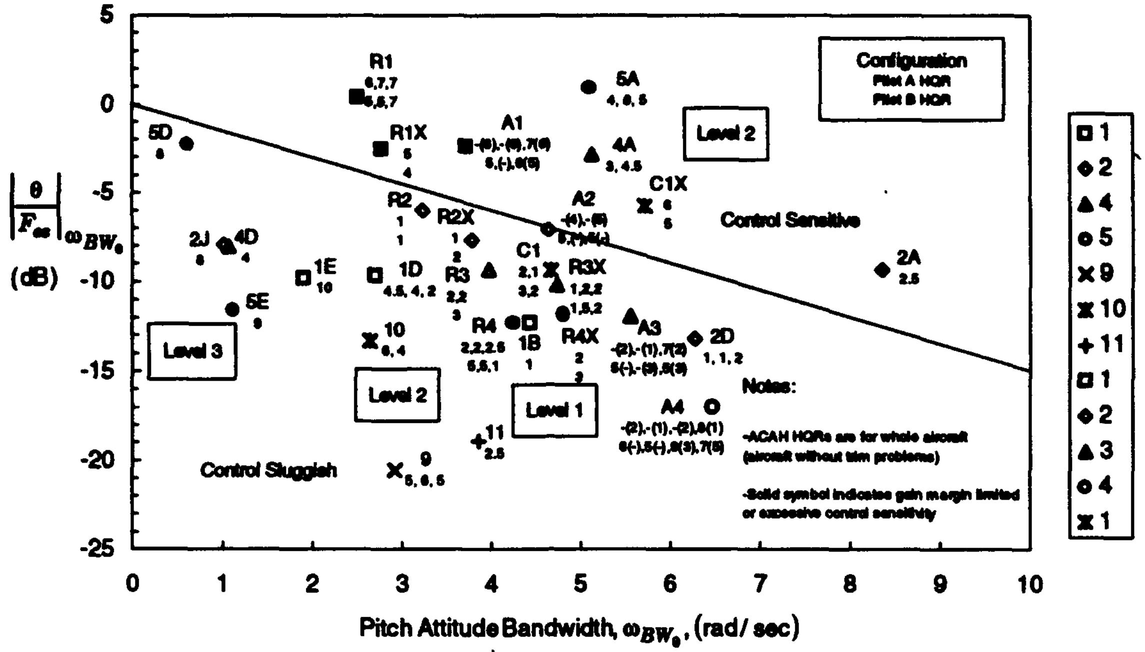

Figure 6.9. θ/F_{es} Control Sensitivity Analysis for Probe and Drogue Air Refueling

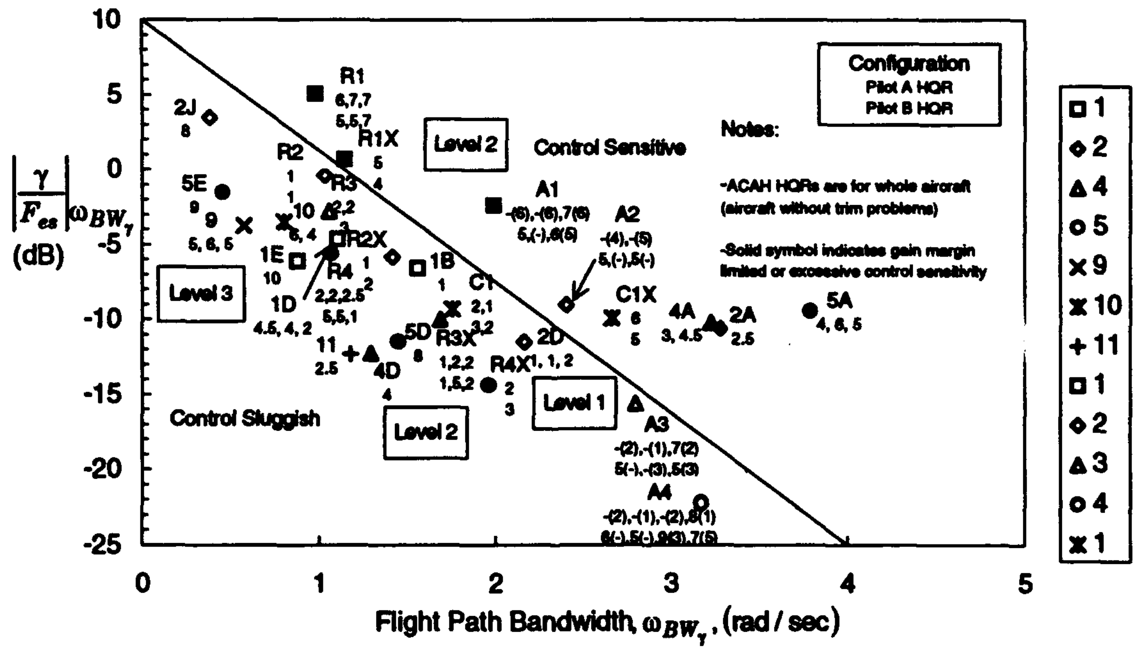

Figure 6.10. γ/F_{es} Control Sensitivity Analysis for Probe and Drogue Air Refueling

VII. Conclusions and Recommendations

7.1 Conclusions

Predictions of flying qualities for small amplitude compensatory tracking tasks such as the probe and drogue air refueling task are best accomplished in the frequency domain. The Bandwidth criterion supplemented with a frequency based control sensitivity metric such as $|\theta/F_{es}|_{\omega_{BW_\theta}}$ or $|\gamma/F_{es}|_{\omega_{BW_\gamma}}$ successfully correlated the observed flying qualities of the twenty eight different configurations (involving three different response-types) flight tested in this experiment and the 1974 Calspan experiment. Configurations with handling qualities deficiencies were characterized by any one of the following[1]: excessive $|\theta/F_{es}|_{\omega_{BW_\theta}}$ or $|\gamma/F_{es}|_{\omega_{BW_\gamma}}$, excessive τ_{p_θ}, low ω_{BW_θ}, or $\omega_{BW_\theta} = \omega_{BW_{gain}}$. General regions of Level 1, 2, and 3 handling qualities are discernible using crossplots of $|\theta/F_{es}|_{\omega_{BW_\theta}}$ vs. ω_{BW_θ} and $|\gamma/F_{es}|_{\omega_{BW_\gamma}}$ vs. ω_{BW_γ}. Although the general trend is clear, more data are required to determine exact boundaries for τ_{p_θ} vs. ω_{BW_θ} or ω_{BW_γ} vs. ω_{BW_θ}.

Short comings of the Bandwidth criterion were identified during analysis of the 1974 Calspan experiment. Considerable information is lost when the characteristics of an entire frequency response are condensed down to one or two numbers. In particular, the Bandwidth criterion failed to identify poor handling qualities for conventional response-types characterized by lightly damped short period dynamics or the improper use of lead compensation. In these cases, the Bandwidth criterion fails to identify the true behavior of θ/F_{es} and γ/F_{es} (important responses to the pilot) deviates substantially from the desired $\cong K/s$ like behavior in the region of piloted crossover. Frequency response information lost

[1]The four ACAH configurations were also deficient due to an improperly mechanized trim system.

can be regained by supplementing the Bandwidth criterion with information on the magnitude of θ/F_{es} and γ/F_{es} in the region of piloted crossover.

Another advantage of supplementing the Bandwidth criterion with information on the magnitudes of θ/F_{es} and γ/F_{es} in the region of piloted crossover, concerns control sensitivity. The Bandwidth criterion is not influenced by command gain selection, however, the pilot is. Excessive command gain, resonance, or the improper use of lead compensation, all result in excessive magnitudes for θ/F_{es} and γ/F_{es} in the region of piloted crossover. In all cases, $|\theta/F_{es}|_{\omega_{BW_\theta}}$ and $|\gamma/F_{es}|_{\omega_{BW_\gamma}}$ were successful at identifying excessive control sensitivity. Requirements for acceptable flight path control sensitivity were particularly tight and $|\gamma/F_{es}|_{\omega_{BW_\gamma}}$ for the best aircraft plotted on a diagonal line.

The time domain based STI Dropback criterion, applicable for quasi open loop flying, is of questionable value for predicting the mid-frequency abruptness tendencies of aircraft engaged in small amplitude compensatory tracking tasks. The STI Dropback criterion emphasizes low to mid-frequency characteristics at the expense of the mid-frequency range characteristics and is not influenced by the command gain selection. The mid-frequency response characteristics (in the region of piloted crossover) were the most important characteristics for this task. Additionally, the time domain nature of the metric makes it difficult to apply in practice.

Excessive $|\theta/F_{es}|$ and $|\gamma/F_{es}|$ in the region of piloted crossover resulted in abrupt responses for all three response-types. High $|\theta/F_{es}|$ and $|\gamma/F_{es}|$ at the low end of the region of piloted crossover resulted in difficulties with flight path control further from the drogue (RCAH such as configuration R3). Low $|\theta/F_{es}|$ and $|\gamma/F_{es}|$ at the low end of the region of piloted crossover gave a feeling of precision pitch and flight path control as well as a feeling of sluggishness (ACAH such as configuration A3). In between was the RCAH extended bandwidth (pseudo conventional) response-type that was very familiar.

The differences between the higher bandwidth RCAH, RCAH extended bandwidth, and ACAH response-types were discernible to the pilot. The RCAH response-types such as

configuration R3 did not allow precise control either at a distance or in close and the compensation techniques were to reference the tanker more and accept a contact within the drogue. The RCAH extended bandwidth response-types such as configuration R3X were very familiar dynamics. These aircraft allowed finer control and no special compensation techniques were required to achieve desired performance. The drogue could be referenced considerably more and contacts with the exact center were possible. The ACAH response-types such as configuration A3 were very different dynamics. They allowed very precise pitch and flight path control and the drogue could be referenced directly. However, there was also a feeling of sluggishness in that the range of pitch attitudes that could be commanded with the stick seemed (and was) small for precise control[2]. There was also a feeling of quickness in the initial response present even in configuration A3. Nonlinear stick shaping may be required to resolve the conflicting requirements of avoiding undesirable pitch accelerations for small stick inputs while still maintaining adequate pitch authority when required.

Inevitably, the question of which response-type was best comes up. Clearly, the RCAH configurations were not as good as the conventional, RCAH extended bandwidth, or potentially, the ACAH response-types. The conventional and RCAH extended bandwidth (pseudo conventional) were essentially identical for this task and were very familiar dynamics that were immediately comfortable for both pilots. Whether the increased precision that the ACAH response-types offered was worth the side effects is undetermined[3]. Future work should focus on the suitability of unconventional response-types to a wide variety of piloting techniques. Ultimately, the best response-type is the one that doesn't require specialized training or familiarity and is *acceptable* to every pilot.

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[2]This problem was compounded by the faulty trim system for the ACAH response-types flight tested in this experiment.

[3]Quickness in the initial response and small range of commandable pitch attitudes.

7.2 Recommendations

Control sensitivity was an important variable in this experiment that *wasn't* optimized for the task in all cases. Fortunately, this turned out to yield valuable information. Recommend future handling qualities investigations use the flexibility offered by variable stability aircraft to select command gains inflight so as to optimize the control sensitivity for the task. This was standard operating procedure for every handling qualities experiment reviewed for this experiment. Until more data is collected to support just what constitutes optimum control sensitivity, it may be detrimental to a handling qualities investigation to fix it.

Recommend the Bandwidth criterion be supplemented with a frequency response based control sensitivity metric. Analysis in this work supports crossplots of $|\theta/F_{es}|_{\omega_{BW_\theta}}$ vs. ω_{BW_θ} and $|\gamma/F_{es}|_{\omega_{BW_\gamma}}$ vs. ω_{BW_γ} as potential control sensitivity metrics. Both of these metrics show an upper limit for $|\theta/F_{es}|_{\omega_{BW_\theta}}$ and $|\gamma/F_{es}|_{\omega_{BW_\gamma}}$ for acceptable control sensitivity. Highly recommend additional work be done to see if this trend is common to other precision tracking tasks as well.

Recommend the pilot ratings in this experiment be taken for what they're worth. Most of the ratings assigned were for an operational task in closely controlled conditions (wings level, little turbulence). While the basic characteristics of the response-types were determined, this was by no means a complete evaluation of these response-types. Future work should look at off nominal conditions. Some HQDT like work was done in this experiment and the handling qualities of the gain margin limited configurations clearly degraded under tight control. Only after looking at all the conditions that could possibly be encountered operationally can the suitability of a response-type be truly determined.

Appendix A. *Stability Derivative Transformation Relationships*

A.1 Longitudinal Stability Derivative Transformation Relationships

The complete transformation from stability axis derivatives to body axis derivatives must consider not only the resolution of the forces and moments but also the perturbed motions and changed inertias. With these considerations, the following relationships exist between body axes, subscript b, and stability axes, no subscript [MAG73, p. 260].

$$
\begin{aligned}
(X_u)_b &= X_u \cos^2\alpha_0 - (X_w + Z_u)\sin\alpha_0 \cos\alpha_0 + Z_w \sin^2\alpha_0 \\
(X_w)_b &= X_w \cos^2\alpha_0 + (X_u - Z_w)\sin\alpha_0 \cos\alpha_0 - Z_u \sin^2\alpha_0 \\
(X_{\dot{w}})_b &= X_{\dot{w}} \cos^2\alpha_0 - Z_{\dot{w}} \sin\alpha_0 \cos\alpha_0 \\
(X_{q;\delta})_b &= X_{q;\delta} \cos\alpha_0 - Z_{q;\delta} \sin\alpha_0 \\
(Z_u)_b &= Z_u \cos^2\alpha_0 - (Z_w - X_u)\sin\alpha_0 \cos\alpha_0 - X_w \sin^2\alpha_0 \\
(Z_w)_b &= Z_w \cos^2\alpha_0 + (Z_u + X_w)\sin\alpha_0 \cos\alpha_0 + X_u \sin^2\alpha_0 \\
(Z_{\dot{w}})_b &= Z_{\dot{w}} \cos^2\alpha_0 + X_{\dot{w}} \sin\alpha_0 \cos\alpha_0 \\
(Z_{q;\delta})_b &= Z_{q;\delta} \cos\alpha_0 + X_{q;\delta} \sin\alpha_0 \\
(M_u)_b &= M_u \cos\alpha_0 - M_w \sin\alpha_0 \\
(M_w)_b &= M_w \cos\alpha_0 + M_u \sin\alpha_0 \\
(M_{\dot{w}})_b &= M_{\dot{w}} \cos\alpha_0 \\
(M_{q;\delta})_b &= M_{q;\delta} \\
(I_{yy})_b &= I_{yy}
\end{aligned}
\tag{A.1}
$$

These equations give body axes dimensional stability derivatives in terms of stability axes dimensional stability derivatives and involve w derivatives. However, the dimensional stability derivatives for the NT-33A are given in terms of a set of body axes while the equations of motion selected for modeling in SIMULINK are referenced to stability axes. The above Eqns can be rewritten using matrix notation and reciprocal relationships

involving α derivatives easily determined as follows (subscript b for body axes and s for stability axes)[1]

$$\begin{bmatrix} X_u \\ X_w \\ Z_u \\ Z_w \end{bmatrix}_b = \begin{bmatrix} \cos^2\alpha_0 & -\sin\alpha_0\cos\alpha_0 & -\sin\alpha_0\cos\alpha_0 & \sin^2\alpha_0 \\ \sin\alpha_0\cos\alpha_0 & \cos^2\alpha_0 & -\sin^2\alpha_0 & -\sin\alpha_0\cos\alpha_0 \\ \sin\alpha_0\cos\alpha_0 & -\sin^2\alpha_0 & \cos^2\alpha_0 & -\sin\alpha_0\cos\alpha_0 \\ \sin^2\alpha_0 & \sin\alpha_0\cos\alpha_0 & \sin\alpha_0\cos\alpha_0 & \cos^2\alpha_0 \end{bmatrix} \begin{bmatrix} X_u \\ X_w \\ Z_u \\ Z_w \end{bmatrix}_s \tag{A.2}$$

$$\begin{bmatrix} X_{\delta_e} \\ Z_{\delta_e} \end{bmatrix}_b = \begin{bmatrix} \cos\alpha_0 & -\sin\alpha_0 \\ \sin\alpha_0 & \cos\alpha_0 \end{bmatrix} \begin{bmatrix} X_{\delta_e} \\ Z_{\delta_e} \end{bmatrix}_s \tag{A.3}$$

$$\begin{bmatrix} M_u \\ M_w \end{bmatrix}_b = \begin{bmatrix} \cos\alpha_0 & -\sin\alpha_0 \\ \sin\alpha_0 & \cos\alpha_0 \end{bmatrix} \begin{bmatrix} M_u \\ M_w \end{bmatrix}_s \tag{A.4}$$

$$[M_{\dot w}]_b = [\cos\alpha_0][M_{\dot w}]_s \tag{A.5}$$

$$[M_{q;\delta}]_b = [M_{q;\delta}]_s \tag{A.6}$$

Each of the above Eqns is in the following form

$$x_b = Tx_s \tag{A.7}$$

where x_b and x_s are vectors of body and stability axes dimensional stability derivatives respectively and T is a transformation matrix relating the two. In Eqn A.6, $T = I$, and $T^{-1} = I$. In Eqn A.5, $T = \cos\alpha_0$, and $T^{-1} = \sec\alpha_0$ (provided $\alpha_0 \neq 90°$). In both Eqn A.3 and Eqn A.4, T is orthogonal and $T^{-1} = T^T$. Although not obvious, but easily verified, T in Eqn A.2 also has the property $T^{-1} = T^T$. So

[1] For the dimensional stability derivatives of interest here.

$$\begin{bmatrix} X_u \\ X_w \\ Z_u \\ Z_w \end{bmatrix}_s = \begin{bmatrix} \cos^2\alpha_0 & \sin\alpha_0\cos\alpha_0 & \sin\alpha_0\cos\alpha_0 & \sin^2\alpha_0 \\ -\sin\alpha_0\cos\alpha_0 & \cos^2\alpha_0 & -\sin^2\alpha_0 & \sin\alpha_0\cos\alpha_0 \\ -\sin\alpha_0\cos\alpha_0 & -\sin^2\alpha_0 & \cos^2\alpha_0 & \sin\alpha_0\cos\alpha_0 \\ \sin^2\alpha_0 & -\sin\alpha_0\cos\alpha_0 & -\sin\alpha_0\cos\alpha_0 & \cos^2\alpha_0 \end{bmatrix} \begin{bmatrix} X_u \\ X_w \\ Z_u \\ Z_w \end{bmatrix}_b \quad \text{(A.8)}$$

$$\begin{bmatrix} X_{\delta_e} \\ Z_{\delta_e} \end{bmatrix}_s = \begin{bmatrix} \cos\alpha_0 & \sin\alpha_0 \\ -\sin\alpha_0 & \cos\alpha_0 \end{bmatrix} \begin{bmatrix} X_{\delta_e} \\ Z_{\delta_e} \end{bmatrix}_b \quad \text{(A.9)}$$

$$\begin{bmatrix} M_u \\ M_w \end{bmatrix}_s = \begin{bmatrix} \cos\alpha_0 & \sin\alpha_0 \\ -\sin\alpha_0 & \cos\alpha_0 \end{bmatrix} \begin{bmatrix} M_u \\ M_w \end{bmatrix}_b \quad \text{(A.10)}$$

$$\left[M_{\dot{w}}\right]_s = \left[\sec\alpha_0\right]\left[M_{\dot{w}}\right]_b \quad \text{(A.11}$$

$$\left[M_{q;\delta}\right]_s = \left[M_{q;\delta}\right]_b \quad \text{(A.12)}$$

Finally, using $X_w = \frac{X_\alpha}{U_0}$, $Z_w = \frac{Z_\alpha}{U_0}$, $M_w = \frac{M_\alpha}{U_0}$, and $M_{\dot{w}} = \frac{M_{\dot{\alpha}}}{U_0}$, the above Eqns become

$$\begin{bmatrix} X_u \\ X_\alpha \\ Z_u \\ Z_\alpha \end{bmatrix}_s = \begin{bmatrix} \cos^2\alpha_0 & \sin\alpha_0\cos\alpha_0 & \sin\alpha_0\cos\alpha_0 & \sin^2\alpha_0 \\ -U_0\sin\alpha_0\cos\alpha_0 & U_0\cos^2\alpha_0 & -U_0\sin^2\alpha_0 & U_0\sin\alpha_0\cos\alpha_0 \\ -\sin\alpha_0\cos\alpha_0 & -\sin^2\alpha_0 & \cos^2\alpha_0 & \sin\alpha_0\cos\alpha_0 \\ U_0\sin^2\alpha_0 & -U_0\sin\alpha_0\cos\alpha_0 & -U_0\sin\alpha_0\cos\alpha_0 & U_0\cos^2\alpha_0 \end{bmatrix} \begin{bmatrix} X_u \\ X_\alpha \\ Z_u \\ Z_\alpha \end{bmatrix}_b \quad \text{(A.13)}$$

$$\begin{bmatrix} X_{\delta_e} \\ Z_{\delta_e} \end{bmatrix}_s = \begin{bmatrix} \cos\alpha_0 & \sin\alpha_0 \\ -\sin\alpha_0 & \cos\alpha_0 \end{bmatrix} \begin{bmatrix} X_{\delta_e} \\ Z_{\delta_e} \end{bmatrix}_b \quad \text{(A.14)}$$

$$\begin{bmatrix} M_u \\ M_\alpha \end{bmatrix}_s = \begin{bmatrix} \cos\alpha_0 & \sin\alpha_0 \\ -U_0\sin\alpha_0 & U_0\cos\alpha_0 \end{bmatrix} \begin{bmatrix} M_u \\ M_\alpha \end{bmatrix}_b \quad \text{(A.15)}$$

$$\left[M_{\dot{w}}\right]_s = \left[U_0\sec\alpha_0\right]\left[M_{\dot{w}}\right]_b \quad \text{(A.16)}$$

$$\left[M_{q;\delta}\right]_s = \left[M_{q;\delta}\right]_b \quad \text{(A.17)}$$

The Eqns A.13 through A.14 were used in a MATLAB M-file to convert body axes dimensional stability derivatives to stability axes dimensional derivatives for use in Eqn 2.7. For small α_0, the transformation matrices in Eqns A.8 through A.12 are approximately I. For large α_0 they become important (i.e., stability axes derivatives are no longer approximately equal to body axes derivatives).

Appendix B. *USAF NT-33A Description*

B.1 Introduction

The NT-33A variable stability aircraft is owned by the USAF (Serial Number 51-4120) and operated by Calspan Advanced Technology Center. It is the oldest aircraft still flying in the USAF. The aircraft was built by Lockheed-Burbank in 1952 and acquired by the Flight Dynamics Directorate in 1955. One of the NT-33A's most obvious modifications was the substitution of an F-94B nose section to provide more volume for instrumentation. After the extensive modifications by Cornell Aeronautical Laboratory (now Calspan Advanced Technology Center), inflight simulations began in 1957.

Since the early 1960's, the NT-33A inflight simulator has been used for the pre first flight evaluation and flight control system development of almost all US fighters and many foreign aircraft as well.

For this project, an F-100 air refueling probe was fitted in the right hand nose gun port. The probe was plugged at the lower end to prevent fuel transfer and other than a new flexible tip, was the same probe used in 1974.

Two different models for the NT-33A were used in this study. Early work was accomplished using stability derivatives published in [Hef72, p.6-31]. Later work was accomplished using a state space description from [Kno86a, p.6]. Both descriptions are documented here.

B.2 NT-33A Stability Derivatives and State Space Description

The NT-33A was modeled in SIMULINK using the state-space representation of Eqn 2.7 for the preliminary work described in Chapter 4. The NT-33A data listed in Table B-1 is from [Hef72, p.22] and is for a nominal cruise configuration (60% internal fuel).

Table B.1. NT-33A Data [Hef72, p.22]

NT-33A Data		
Parameter	Value	Units
S	234.8	ft^2
b	37.54	ft
c	6.72	ft
W	13,700	lb
cg[1]	0.263	% MAC
I_{xx}	23,801	$slug - ft^2$
I_{yy}	21,101	$slug - ft^2$
I_{zz}	43,802	$slug - ft^2$
I_{xz}	480	$slug - ft^2$
ε [2]	-1.37	deg
x_a [3]	6.53	ft

A flight condition of Mach 0.55 (252 KIAS) at 20,000 ft was selected for air refueling. Flight condition specifics are listed in Table B.2.

Table B.2. Flight Condition Parameters [Hef72, p.22]

Flight Condition Parameters		
Parameter	Value	Units
h	20,000	ft
M	0.55	—
V	570	ft/sec
V	252	KCAS
q	206	lb/ft^2
α_0	0.8	deg

---

[1]Relative to the mean aerodynamic chord (MAC)

[2]Inclination of principle axis with respect to the fuselage reference line.

[3]Distance from the cg to the pilot.

The dimensional stability derivatives (body axis system) for this flight condition are listed in Table B.3 [Hef72, p.23].

Table B.3. NT-33A Dimensional Stability Derivatives [Hef72, p.23]

NT-33A Dimensional Stability Derivatives (Body axis system)		
Derivative	Value	Units
X_u	−7.3500e−03	$\frac{1}{\text{sec}}$
X_w	3.9100e−02	$\frac{1}{\text{sec}}$
X_{δ_e}	5.0000e−01	$\frac{\text{ft}}{\text{rad-sec}^2}$
Z_u	−1.0700e−01	$\frac{1}{\text{sec}}$
Z_w	−1.2500e+00	$\frac{1}{\text{sec}}$
Z_{δ_e}	−4.0900e+01	$\frac{\text{ft}}{\text{rad-sec}^2}$
M_u	−1.8300e−03	$\frac{1}{\text{ft-sec}}$
M_w	−1.5700e−02	$\frac{1}{\text{ft-sec}}$
$M_{\dot{w}}$	−5.4100e−04	$\frac{1}{\text{ft}}$
M_q	−9.8100e−01	$\frac{1}{\text{sec}}$
M_{δ_e}	−1.4200e+01	$\frac{1}{\text{rad-sec}^2}$

These stability derivatives are referenced to body axes aligned with the thrust vector and need to be transformed from this body axis system to the stability axis system before they can be used in Eqn 2.7. Since the trim angle of attack (AOA) at this flight condition is small ($\alpha_0 = 0.8°$), an excellent approximation would be to use the body axis system dimensional stability derivatives in Eqn 2.7 without first transforming them (i.e., assume the stability axis system dimensional stability derivatives are approximately equal to the body axis system dimensional stability derivatives). However, before this flight condition was selected, the appropriate transformations were developed and coded in a MATLAB M-file to automatically perform the conversion. The transformations are described in detail

in Appendix A. The dimensional stability derivatives (stability axes) are (with $U_0 = 570$ fps) listed in Table B.4.

Table B.4. NT-33A Dimensional Stability Derivatives

NT-33A Dimensional Stability Derivatives (Stability axis system)		
Derivative	Value	Units
X_u	-8.5402e-03	$\frac{1}{sec}$
X_α	1.2406e+01	$\frac{ft}{sec^2}$
X_{δ_e}	-7.1102e-02	$\frac{ft}{rad-sec^2}$
Z_u	-1.2434e-01	$\frac{1}{sec}$
Z_w	-1.2488e+02	$\frac{ft}{sec^2}$
Z_{δ_e}	-4.0903e+01	$\frac{ft}{rad-sec^2}$
M_u	-4.0219e-04	$\frac{1}{ft-sec}$
M_α	-8.9467e+00	$\frac{1}{sec^2}$
$M_{\dot{w}}$	-5.411e-04	$\frac{1}{ft}$
$M_{\dot{\alpha}}$	-3.0840e-01	$\frac{1}{sec}$
M_q	-9.8100e-01	$\frac{1}{sec}$
M_{δ_e}	-1.4200e+01	$\frac{1}{rad-sec^2}$

The stability derivatives listed in Table B.4 are substituted into Eqn 2.7 to realize a fourth order state space description of the NT-33A dynamics. A similarity transformation [Oga90, p.913] was used to transform the A and B matrices of Eqn 2.7 so angles are in degrees instead of radians and angular rates are in deg/sec instead of rad/sec. Let the state space representation of Eqn 2.7 be

$$\dot{z} = \hat{A}z + \hat{B}v \tag{B.1}$$

Let the transformation matrix T relate the state vectors x and z

$$x = \begin{bmatrix} \alpha & (\text{deg}) \\ \theta & (\text{deg}) \\ q & (\frac{\text{deg}}{\text{sec}}) \\ u & (\frac{\text{ft}}{\text{sec}}) \end{bmatrix} = \begin{bmatrix} \frac{180}{\pi} & 0 & 0 & 0 \\ 0 & \frac{180}{\pi} & 0 & 0 \\ 0 & 0 & \frac{180}{\pi} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \alpha & (\text{rad}) \\ \theta & (\text{rad}) \\ q & (\frac{\text{rad}}{\text{sec}}) \\ u & (\frac{\text{ft}}{\text{sec}}) \end{bmatrix} = Tz \tag{B.2}$$

and the transformation matrix Q relate the control variables u and v

$$u = \left[\delta_e \quad (\text{deg})\right] = \left[\frac{180}{\pi}\right]\left[\delta_e \quad (\text{rad})\right] = Qv \tag{B.3}$$

So

$$z = T^{-1}x \tag{B.4}$$

$$v = Q^{-1}u \tag{B.5}$$

Substituting Eqns B.4 and B.5 into Eqn B.1 gives

$$T^{-1}\dot{x} = \hat{A}T^{-1}x + \hat{B}Q^{-1}u \tag{B.6}$$

and

$$\dot{x} = T\hat{A}T^{-1}x + T\hat{B}Q^{-1}u = A_{NT\text{-}33A}x + B_{NT\text{-}33A}u \tag{B.7}$$

Where $A_{NT\text{-}33A}$ and $B_{NT\text{-}33A}$ are

$$A_{NT\text{-}33A} = \begin{bmatrix} -1.2488e+00 & 0 & 1 & -1.2498e-02 \\ 0 & 0 & 1 & 0 \\ -8.5615e+00 & 0 & -1.2894e+00 & -1.9189e-02 \\ 2.1652e-01 & -5.6200e-01 & 0 & -8.5402e-03 \end{bmatrix} \tag{B.8}$$

$$B_{NT\text{-}33A} = \begin{bmatrix} -7.1760e-02 \\ 0 \\ -1.4178e+01 \\ -1.2410e-03 \end{bmatrix} \tag{B.9}$$

With state vector

$$x = \begin{bmatrix} \alpha & (\text{deg}) \\ \theta & (\text{deg}) \\ q & (\text{deg/sec}) \\ u & (\text{ft/sec}) \end{bmatrix} \tag{B.10}$$

B.3 NT-33A State Space Description

The NT-33A was modeled in SIMULINK using the state-space representation of Eqn 2.8 for the final work described in Chapter 5. The state space representation of the NT-33A given by Eqn B.15 is from [Kno86a, p.6] and is for a cruise condition at 10,000 ft PA, 250 KIAS, with 450 gallons of fuel remaining.

$$A_{NT-33A} = \begin{bmatrix} -3.2000e-02 & 8.3000e-02 & -2.6000e-02 & -6.5000e-02 \\ -1.3000e-01 & -1.2300e+00 & 1 & -2.0000e-03 \\ 6.8000e-02 & -3.9300e+00 & -1.8300e+00 & -1.0000e-03 \\ 0 & 0 & 1 & 0 \end{bmatrix} \tag{B.11}$$

$$B_{NT-33A} = \begin{bmatrix} 1.0000e-03 \\ -5.3000e-02 \\ -7.7500e+00 \\ 0 \end{bmatrix} \tag{B.12}$$

With state vector

$$w = \begin{bmatrix} u & (\text{ft/sec}) \\ \alpha & (\text{rad}) \\ q & (\text{rad/sec}) \\ \theta & (\text{rad}) \end{bmatrix} \tag{B.13}$$

In order to take advantage of the SIMULINK block diagrams constructed for the earlier work, Eqns B.11 and B.12 were transformed so the state vector was the same as Eqn B.10. Let

$$\dot{w} = \tilde{A}w + \tilde{B}v \tag{B.14}$$

where $\tilde{A} = A_{NT-33A}$ and $\tilde{B} = B_{NT-33A}$ are Eqns B.11 and B.12 respectively. To rearrange the states, let

$$z = \begin{bmatrix} \alpha \\ \theta \\ q \\ u \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} u \\ \alpha \\ q \\ \theta \end{bmatrix} = Rw \tag{B.15}$$

so

$$w = R^{-1}z \tag{B.16}$$

Substituting Eqn B.16 into Eqn B.14 gives

$$R^{-1}\dot{z} = \tilde{A}R^{-1}z + \tilde{B}v \tag{B.17}$$

and so

$$\dot{z} = R\tilde{A}R^{-1}z + R\tilde{B}v \tag{B.18}$$

Eqn B.18 is the same form as Eqn B.1. Letting $\hat{A} = R\tilde{A}R^{-1}$ and $\hat{B} = R\tilde{B}$ and using the same steps as Eqns B.2 through B.7 gives

$$\dot{x} = TR\tilde{A}R^{-1}T^{-1}x + TR\tilde{B}Q^{-1}u = A_{NT-33A}x + B_{NT-33A}u \tag{B.19}$$

Where A_{NT-33A} and B_{NT-33A} are now

$$A_{NT\text{-}33A} = \begin{bmatrix} -1.2300e+00 & -2.0000e-03 & 1 & -7.4485e+02 \\ 0 & 0 & 1 & 0 \\ -3.9300e+00 & -1.0000e-03 & -1.8300e+00 & 3.8961e+00 \\ 1.4486e-03 & -1.1345e-03 & -4.5379e-04 & -3.2000e-02 \end{bmatrix} \quad \text{(B.20)}$$

$$B_{NT\text{-}33A} = \begin{bmatrix} -5.3000e-02 \\ 0 \\ -7.7500e+00 \\ 1.7453e-05 \end{bmatrix} \quad \text{(B.21)}$$

With state vector

$$x = \begin{bmatrix} \alpha & \text{(deg)} \\ \theta & \text{(deg)} \\ q & \text{(deg/sec)} \\ u & \text{(ft/sec)} \end{bmatrix} \quad \text{(B.22)}$$

B.4 NT-33A Simulation Method and Data Recording Capability

The different FCS configurations were stored in the VSS computer memory as experiment numbers and were recalled inflight from the rear cockpit by the safety pilot. With the VSS engaged, the evaluation pilot in the front cockpit controlled the aircraft through a center stick controller. The VSS received electrical inputs from the evaluation pilot's controls, alpha vane, beta probe, rate gyros, and accelerometers. The elevator, rudder, and ailerons were connected to individual hydraulic servos which were controlled by the VSS.

The NT-33A was instrumented with a Calspan designed data acquisition system (DAS), headup display (HUD) video tape recorder, and a cassette voice recorder. Data were sampled at a rate of 100 samples per second and were recorded on a 10.5 inch reel tape using a twenty eight channel Ampex AR-700 flight recorder. Key parameters recorded

during the evaluation are listed in Table B.5. Approximately two hours of recording time were available with a standard tape. The DAS recorder control panel (RCP) was also designed by Calspan and was located in the rear cockpit of the NT-33A. A flight record number was set on the RCP and recorded on the DAS tape to assist in identifying data collected. A record number was recorded on the DAS tape and was automatically incremented during recorder ON and OFF commands.

Table B.5. NT-33A Data Parameter List

NT-33A Data Parameter List				
Parameter	Units	Range	Resolution	Accuracy
Record number	—	0 to 999	—	—
Indicated airspeed, KIAS	knots	25 to 275	0.13	0.50
True airspeed, KTAS	knots	0 to 592	0.30	1.2
Pressure altitude, H_c	ft	0 to 25,000	6.5	26
Longitudinal stick force, F_{es}	lb	–100 to +100	0.050	0.20
Longitudinal stick deflection, δ_{es}	in	–10 to +10	0.005	0.020
Elevator deflection, δ_e	deg	–40 to +40	0.020	0.080
Pitch rate, q	deg/sec	–50 to +50	0.025	0.10
Pitch attitude, θ	deg	–90 to +90	0.03	0.11
AOA, α	deg	–20 to +20	0.10	0.40
Normal acceleration, n_{z_p}	g	–5 to +5	0.0025	0.010
Normal acceleration, $n_{z_{cg}}$	g	–5 to +5	0.0025	0.010
Event marker	—	0 or 1	—	—

Appendix C. *State-Space Realizations of Transfer Functions*

C.1 State-Space Realizations of Transfer Functions

Applying the Laplace Transform to the standard state-space differential equation yields the transfer function matrix from the input vector u to the output vector y in terms of the state matrices

$$\begin{aligned} \dot{x} &= Ax + Bu \quad \Rightarrow \quad sX(s) = AX(s) + BU(s) \\ y &= Cx + Du \quad \Rightarrow \quad Y(s) = CX(s) + DU(s) \end{aligned} \tag{C.1}$$

so

$$Y(s) = \left[C(sI - A)^{-1}B + D\right]U(s) = G(s)U(s) \tag{C.2}$$

The transfer function matrix G(s) in terms of state matrices is[1]

$$G(s) = C(sI - A)^{-1}B + D \equiv \left[\begin{array}{c|c} A & B \\ \hline C & D \end{array}\right] \tag{C.3}$$

Complicated systems are built from simpler systems by applying simple rules. Scalar multiplication gives

$$\alpha G(s) = \alpha\left[\begin{array}{c|c} A & B \\ \hline C & D \end{array}\right] = \left[\begin{array}{c|c} A & \alpha B \\ \hline C & \alpha D \end{array}\right] = \left[\begin{array}{c|c} A & B \\ \hline \alpha C & \alpha D \end{array}\right] \tag{C.4}$$

Series connection gives

$$G_2(s)G_1(s) = \left[\begin{array}{c|c} A_2 & B_2 \\ \hline C_2 & D_2 \end{array}\right]\left[\begin{array}{c|c} A_1 & B_1 \\ \hline C_1 & D_1 \end{array}\right] = \left[\begin{array}{cc|c} A_2 & B_2C_1 & B_2D_1 \\ 0 & A_1 & B_1 \\ \hline C_2 & D_2C_1 & D_2D_1 \end{array}\right] = \left[\begin{array}{cc|c} A_1 & 0 & B_1 \\ B_2C_1 & A_2 & B_2D_1 \\ \hline D_2C_1 & C_2 & D_2D_1 \end{array}\right] \tag{C.5}$$

[1]This notation denotes a transfer function, not a block 2×2 real matrix

C.2 State-Space Realization of Short Period Approximation Transfer Functions

Given the following short period approximation transfer functions for α and q

$$\frac{\alpha(s)}{\delta_e(s)}=\frac{M_{\delta_e}}{s^2+2\zeta_{sp}\omega_{sp}s+\omega_{sp}^2} \qquad \left(\frac{\text{deg}}{\text{deg}}\right) \tag{C.6}$$

$$\frac{q(s)}{\delta_e(s)}=\frac{M_{\delta_e}\left(s+\frac{1}{T_{\theta_2}}\right)}{s^2+2\zeta_{sp}\omega_{sp}s+\omega_{sp}^2} \qquad \left(\frac{\frac{\text{deg}}{\text{sec}}}{\text{deg}}\right) \tag{C.7}$$

A state-space representation with states α and q can be determined using the following A and B matrices

$$A=\begin{bmatrix} 0 & 1 \\ -\omega_{sp}^2 & -2\zeta_{sp}\omega_{sp} \end{bmatrix} \tag{C.8}$$

$$B=\begin{bmatrix} 0 \\ 1 \end{bmatrix} \tag{C.9}$$

together with the transformation matrix

$$T=\begin{bmatrix} M_{\delta_e} & 0 \\ \frac{M_{\delta_e}}{T_{\theta_2}} & M_{\delta_e} \end{bmatrix} \tag{C.10}$$

and inverse transformation matrix

$$T^{-1}=\begin{bmatrix} \frac{1}{M_{\delta_e}} & 0 \\ -\frac{1}{M_{\delta_e}T_{\theta_2}} & \frac{1}{M_{\delta_e}} \end{bmatrix} \tag{C.11}$$

The state-space representation is

$$G(s)=\left[\begin{array}{c|c} TAT^{-1} & TB \\ \hline I & 0 \end{array}\right]=\left[\begin{array}{cc|c} -\frac{1}{T_{\theta_2}} & 1 & 0 \\ \left(-\frac{1}{T_{\theta_2}^2}-\omega_{sp}^2+\frac{2\zeta_{sp}\omega_{sp}}{T_{\theta_2}}\right) & \left(\frac{1}{T_{\theta_2}}-2\zeta_{sp}\omega_{sp}\right) & M_{\delta_e} \\ \hline 1 & 0 & 0 \\ 0 & 1 & 0 \end{array}\right] \tag{C.12}$$

with states α and q.

C.3 State-Space Realizations of Common Flight Control System Transfer Functions

The following is a collection of the state-space representations for FCS transfer functions used in SIMULINK. The state-space representations are controllable canonical forms multiplied by a scalar, α.

First order system ($\alpha = 1/T$)

$$G(s) = \frac{1}{(Ts+1)} = \frac{1}{T}\frac{1}{\left(s+\frac{1}{T}\right)} \equiv \left[\begin{array}{c|c} -\frac{1}{T} & \frac{1}{T} \\ \hline 1 & 0 \end{array}\right] \tag{C.13}$$

Second order system ($\alpha = \omega_n^2$)

$$G(s) = \frac{1}{\left[\frac{s^2}{\omega_n^2} + \frac{2\zeta_n}{\omega_n}s + 1\right]} = \omega_n^2 \frac{1}{\left[s^2 + 2\zeta_n\omega_n + \omega_n^2\right]} \equiv \left[\begin{array}{cc|c} 0 & 1 & 0 \\ -\omega_n^2 & -2\zeta_n\omega_n & \omega_n^2 \\ \hline 1 & 0 & 0 \end{array}\right] \tag{C.14}$$

Equalization ($\alpha = K_q/T_q$)

$$G(s) = K_q + \frac{K_q}{T_q}\frac{1}{s} = \frac{K_q\left(s+\frac{1}{T_q}\right)}{s} = \frac{K_q}{T_q}\frac{(T_q s+1)}{s} \equiv \left[\begin{array}{c|c} 0 & \frac{K_q}{T_q} \\ \hline 1 & K_q \end{array}\right] \tag{C.15}$$

Washout filter ($\alpha = -1/T_{wo}$)

$$G(s) = \frac{T_{wo}s}{(T_{wo}s+1)} = \frac{s}{\left(s+\frac{1}{T_{wo}}\right)} = -\frac{1}{T_{wo}}\frac{-T_{wo}s}{\left(s+\frac{1}{T_{wo}}\right)} \equiv \left[\begin{array}{c|c} -\frac{1}{T_{wo}} & -\frac{1}{T_{wo}} \\ \hline 1 & 1 \end{array}\right] \tag{C.16}$$

First order lead or lag filter ($\alpha = (\tau_2 - \tau_1)/\tau_2^2$)

$$G(s) = \frac{(\tau_1 s+1)}{(\tau_2 s+1)} = \frac{\tau_1}{\tau_2}\frac{\left(s+\frac{1}{\tau_1}\right)}{\left(s+\frac{1}{\tau_2}\right)} = \frac{\tau_2-\tau_1}{\tau_2^2}\frac{\left(\frac{\tau_1\tau_2}{\tau_2-\tau_1}s + \frac{\tau_2}{\tau_2-\tau_1}\right)}{\left(s+\frac{1}{\tau_2}\right)} \equiv \left[\begin{array}{c|c} -\frac{1}{\tau_2} & \frac{\tau_2-\tau_1}{\tau_2^2} \\ \hline 1 & \frac{\tau_1}{\tau_2} \end{array}\right] \tag{C.17}$$

where $\tau_1 > \tau_2 \rightarrow$ lead and $\tau_1 < \tau_2 \rightarrow$ lag.

Derivative approximation ($\alpha = -1/\tau^2$)

$$G(s) = \frac{s}{(\tau s+1)} = \frac{1}{\tau}\frac{s}{\left(s+\frac{1}{\tau}\right)} = -\frac{1}{\tau^2}\frac{-\tau s}{\left(s+\frac{1}{\tau}\right)} \equiv \left[\begin{array}{c|c} -\frac{1}{\tau} & -\frac{1}{\tau^2} \\ \hline 1 & \frac{1}{\tau} \end{array}\right] \tag{C.18}$$

where $\tau \ll 1$.

First order Padé approximation ($\alpha = 4/\tau$)

$$G(s) = e^{-\tau s} \cong \frac{1-\frac{\tau s}{2}}{1+\frac{\tau s}{2}} = -\frac{\left(s-\frac{2}{\tau}\right)}{\left(s+\frac{2}{\tau}\right)} = \frac{4}{\tau}\frac{\left(-\frac{\tau}{4}s+\frac{1}{2}\right)}{\left(s+\frac{2}{\tau}\right)} \equiv \left[\begin{array}{c|c} -\frac{2}{\tau} & \frac{4}{\tau} \\ \hline 1 & -1 \end{array}\right] \tag{C.19}$$

RCAH prefilter

$$G(s) = 1 \tag{C.20}$$

RCAH extended bandwidth prefilter ($\alpha = \left(T_q - T_1\right)/T_q T_1$)

$$G(s) = \frac{(s+\frac{1}{T_1})}{(s+\frac{1}{T_q})} = \frac{\left(T_q - T_1\right)}{T_q T_1}\frac{\left(\frac{T_q T_1}{T_q - T_1}s + \frac{T_q}{T_q - T_1}\right)}{(s+\frac{1}{T_q})} \equiv \left[\begin{array}{c|c} -\frac{1}{T_q} & \frac{(T_q - T_1)}{T_q T_1} \\ \hline 1 & 1 \end{array}\right] \tag{C.21}$$

where $1/T_1$ is near, but less than $1/T_q$; $1/T_1 \to 1/T_{\theta_2}$ (pseudo conventional).

ACAH prefilter ($\alpha = -1/T_q$)

$$G(s) = \frac{s}{\left(s+\frac{1}{T_q}\right)} = -\frac{1}{T_q}\frac{-T_q s}{\left(s+\frac{1}{T_q}\right)} \equiv \left[\begin{array}{c|c} -\frac{1}{T_q} & -\frac{1}{T_q} \\ \hline 1 & 1 \end{array}\right] \tag{C.22}$$

Appendix D. *Calspan Configurations*

D.1 Introduction

The 1974 Calspan configurations were modeled in SIMULINK using the equations of motion described here. Several transfer functions relating the output quantities of interest to the pilot's stick force input are required. To keep the block diagrams to a reasonable size, these transfer functions were transformed into state-space representations using the transformations described in Appendix C. State-space matrices are treated as variables in the SIMULINK block diagrams and defined in script MATLAB M-files.

D.2 Calspan Configurations

D.2.1 Four Basic Short Period Configurations Four basic short-period configurations were used to provide a baseline range of aircraft dynamics. Seven other configurations were developed from these baseline aircraft by adding flight control system dynamics (a first order lead or lag) in the command path. This effectively shaped the pilot's input and significantly altered the aircraft's short-term response. Figure D.1 is a SIMULINK block diagram of these eleven configurations.

The following gains, transfer functions, and state-representations describe the dynamics for each of the blocks in Figure D.1. The transfer functions were converted into state space representations for use in SIMULINK. State space realizations of transfer functions are given in Appendix C.

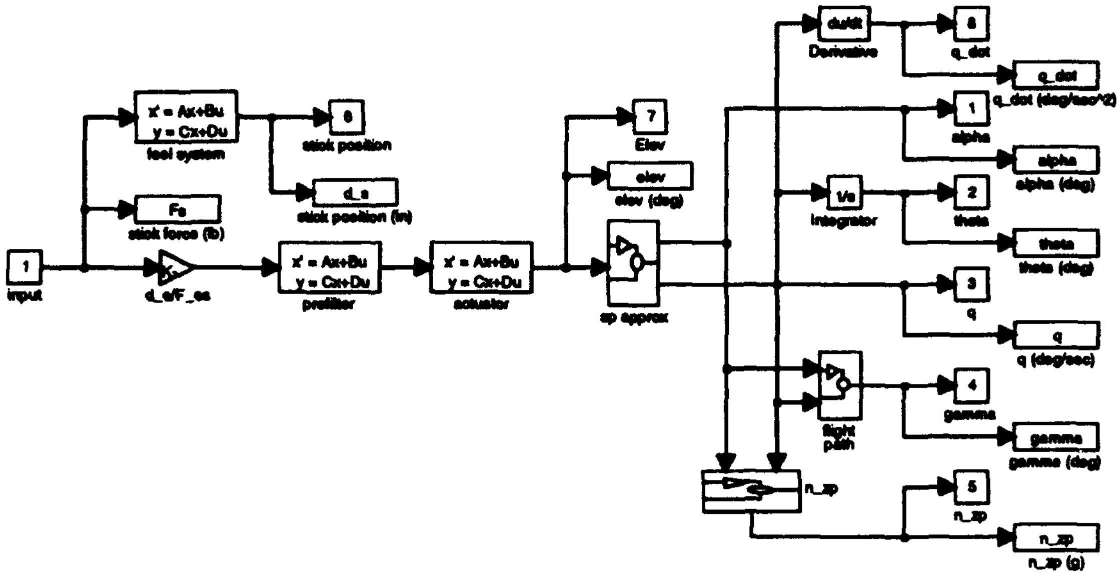

Figure D.1. SIMULINK Block Diagram of Calspan Configurations

The closed-loop dynamics of the simulated airframe plus FCS were given as [BCC74, p.5]

$$\frac{\theta(s)}{F_{es}(s)} = \frac{K_\theta(\tau_1 s+1)(T_{\theta_2} s+1)}{(\tau_2 s+1)\left[\frac{s^2}{\omega_3^2}+\frac{2\zeta_3}{\omega_3}s+1\right]\left[\frac{s^2}{\omega_{sp}^2}+\frac{2\zeta_{sp}}{\omega_{sp}}s+1\right]s} \quad \frac{\text{deg}}{\text{lb}} \tag{D.1}$$

Pilot inputs were via a force command center stick with simulated feel system dynamics given by [BCC74, p.30]

$$\frac{\delta_s(s)}{F_{es}(s)} = \frac{0.046}{\frac{s^2}{(31.0)^2}+\frac{2(1.0)}{(31.0)}s+1.0} \quad \frac{\text{in}}{\text{lb}} \tag{D.2}$$

The elevator stick static force gradient was 22 lb/in and no longitudinal friction and breakout forces were published (and assumed to be zero here).

For purposes of modeling in SIMULINK, Eqn D.1 was separated into individual transfer functions representing the FCS dynamics, actuator dynamics, and the aircraft short period dynamics and rewritten as follows

$$\frac{\theta(s)}{F_{es}(s)} = \frac{(\tau_1 s+1)}{(\tau_2 s+1)} \frac{\omega_3^2}{\left[s^2+2\zeta_3\omega_3 s+\omega_3^2\right]} \frac{K_\theta \omega_{sp}^2 T_{\theta_2}\left(s+\frac{1}{T_{\theta_2}}\right)}{s\left[s^2+2\zeta_{sp}\omega_{sp}s+\omega_{sp}^2\right]} \qquad \frac{\text{deg}}{\text{lb}} \tag{D.3}$$

Since the gain K_θ was not published for any of the configurations, it's convenient to separate the short period transfer function gain into two gains. Let

$$K_\theta \omega_{sp}^2 T_{\theta_2} = \left(\frac{\delta_e}{F_{es}}\right)_{ss} M_{\delta_e} = M_{F_{es}} \qquad \frac{\text{deg}}{\text{lb-sec}^2} \tag{D.4}$$

The gain $(\delta_e/F_{es})_{ss}$ is the steady-state gearing between the elevator deflection and the longitudinal stick force input and the control derivative, M_{δ_e}, is the elevator control power. The $(\delta_e/F_{es})_{ss}$ gain is modeled in the command path (before the actuator) while M_{δ_e} is contained in the aircraft short period approximation. Using both $(\delta_e/F_{es})_{ss}$ and M_{δ_e} allows plotting realistic elevator deflections in addition to the motion variables. Several calculations are required to determine values for $(\delta_e/F_{es})_{ss}$ and M_{δ_e}. These calculations are performed in subsection D.1.3 and the $(\delta_e/F_{es})_{ss}$ for each configuration is listed in Table D.1.

The FCS dynamics (prefilter) were of the form

$$G(s) = 1 \tag{D.5}$$

for the core (baseline) configurations (configurations 1D, 2D, 4A, and 5A), and

$$G(s) = \frac{(\tau_1 s+1)}{(\tau_2 s+1)} \tag{D.6}$$

for configurations with added dynamics (configurations 1B, 2A, 4D, 5D, 2J, 5E, and 1E). Values for τ_1 and τ_2 varied from 0 to ∞ and their reciprocals are listed in Table D.1. The actuator dynamics were

$$\frac{\delta_e(s)}{\delta_{e_c}(s)} = \frac{63.0^2}{s^2+2(0.75)(63.0)s+63.0^2} \qquad \frac{\text{deg}}{\text{deg}} \tag{D.7}$$

The aircraft short period dynamics were

$$\frac{\theta(s)}{\delta_e(s)} = \frac{M_{\delta_e}\left(s + \frac{1}{T_{\theta_2}}\right)}{s\left[s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2\right]} \qquad \frac{\text{deg}}{\text{deg}} \tag{D.8}$$

However, Eqn D.8 only relates the pitch attitude to the elevator deflection. By assuming the other short period approximation relations are also valid, considerably more information becomes available. The aircraft dynamics were modeled as

$$\frac{\alpha(s)}{\delta_e(s)} = \frac{M_{\delta_e}}{s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2} \qquad \frac{\text{deg}}{\text{deg}} \tag{D.9}$$

$$\frac{q(s)}{\delta_e(s)} = \frac{M_{\delta_e}\left(s + \frac{1}{T_{\theta_2}}\right)}{s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2} \qquad \frac{\frac{\text{deg}}{\text{sec}}}{\text{deg}} \tag{D.10}$$

The state space representation of these two transfer functions is described in Appendix C. Values for ζ_{sp} and ω_{sp} for each configuration are listed in Table D.1.

The relations developed so far relate δ_s, δ_e, α, and q, to the pilot's stick force input. The other variables of interest (θ, γ, n_{z_p}, and $\dot{q}$) were determined using the following relationships valid for wings level flight.

Pitch rate was integrated once to get pitch attitude.

$$\theta(s) = \frac{1}{s}q(s) \qquad \text{deg} \tag{D.11}$$

Pitch attitude and angle of attack were differenced to get the flight path dynamics.

$$\gamma(s) = \theta(s) - \alpha(s) \qquad \text{deg} \tag{D.12}$$

For $\gamma_0 = 0$, the normal acceleration at a distance, x_a, forward of the center of gravity (x_a=6.53 ft and is positive forward) is approximated by [MAG73, p. 446]

$$a_z = U_0(\dot{\alpha} - q) - x_a\dot{q} \qquad \frac{\text{ft}}{\text{sec}^2} \tag{D.13}$$

The incremental load factor at the pilot station (positive for a pullup) is related to the normal acceleration by

$$n_{z_p}(s) = -\frac{a_{z_p}(s)}{g} = -\frac{1}{g}\left[U_0(s\alpha(s) - q(s)) - x_a sq(s)\right] \quad g \tag{D.14}$$

For the NT-33A, $x_a = 6.53$ ft. [Hef72, p.22]. Finally, pitch rate is differentiated once to get pitch acceleration dynamics.

$$\ddot{\theta}(s) = sq(s) \qquad \frac{\deg}{\sec^2} \tag{D.15}$$

For frequency responses, the derivatives in Eqns D.14 and D.15 were approximated by

$$s \equiv \frac{s}{\tau s + 1} \tag{D.16}$$

where $\tau = 1e-05 << 1$ was used (derivative blocks in Figures D.1 and D.2 were approximated with Eqn D.16).

D.2.2 Three Additional Short Period Configurations Three additional short period configurations were also flight tested. These configurations had rather extreme combinations of ζ_{sp} and ω_{sp} to compare with the short period requirements of MIL-F-8785B in areas where the data supporting the requirements were sparse. To make the control system characteristics of these configurations compatible with the control systems for which most of the specification data was obtained, stick position commands were used instead of stick force commands as was used by the other eleven configurations [NS70, p.11]. Figure D.2 is a SIMULINK block diagram of these three configurations (configurations 9, 10, and 11).

The gains, transfer functions, and state-representations described in the previous subsection apply for similarly labeled blocks with the following exceptions. The transfer functions were converted into state space representations for use in SIMULINK. State space realizations of transfer functions are given in Appendix C.

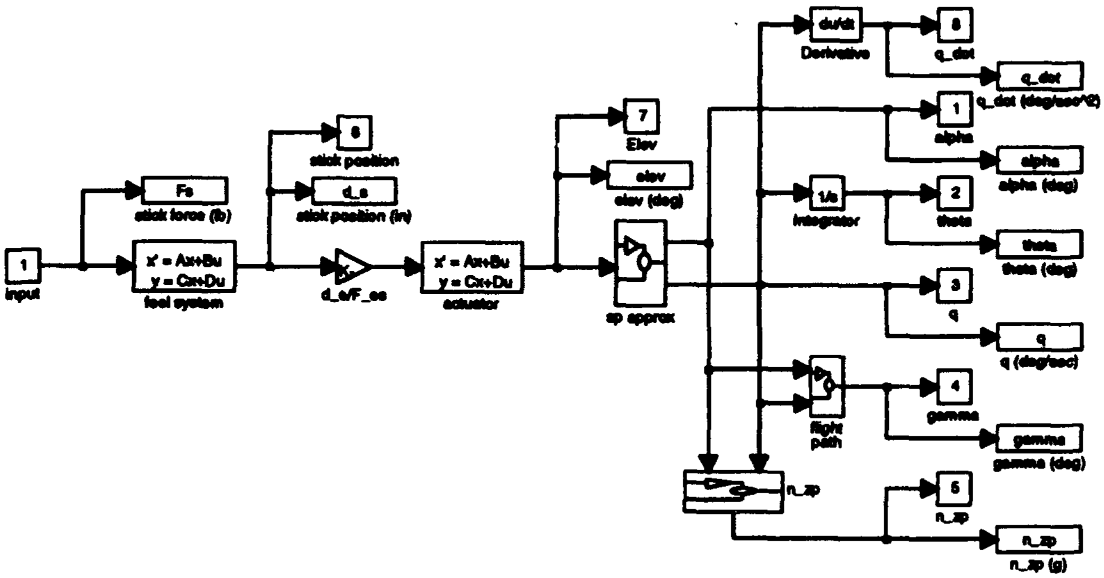

Figure D.2. SIMULINK Block Diagram of Calspan Configurations (Position Controller)

The simulated airframe plus flight control system was given by [BCC74, p.8]

$$\frac{\theta(s)}{F_{es}(s)} = \frac{\delta_{es}(s)}{F_{es}(s)} \frac{K'_\theta\left(T_{\theta_2}s+1\right)}{\left[\frac{s^2}{\omega_3^2}+\frac{2\zeta_3}{\omega_3}s+1\right]\left[\frac{s^2}{\omega_{sp}^2}+\frac{2\zeta_{sp}}{\omega_{sp}}s+1\right]s} \qquad \frac{\text{deg}}{\text{in}} \tag{D.17}$$

For purposes of modeling in SIMULINK, the transfer function in Eqn D.17 was separated into individual transfer functions representing the feel system, actuator dynamics, and the aircraft short period dynamics and rewritten as follows

$$\frac{\theta(s)}{F_{es}(s)} = \frac{0.046(31.0)^2}{\left[s^2+2(1.0)(31.0)s+(31.0)^2\right]} \frac{\omega_3^2}{\left[s^2+2\zeta_3\omega_3 s+\omega_3^2\right]} \frac{K'_\theta\omega_{sp}^2 T_{\theta_2}\left(s+\frac{1}{T_{\theta_2}}\right)}{s\left[s^2+2\zeta_{sp}\omega_{sp}s+\omega_{sp}^2\right]} \qquad \frac{\text{deg}}{\text{lb}}$$

(D.18)

The simulated feel system dynamics are the same as before (Eqn D.2), except now they are in the command path. Since the gain K'_θ was not published for any of the configurations, it's again convenient to separate the transfer function gain into two gains. Let

$$0.046K'_{\theta}\omega_{sp}^{2}T_{\theta_2} = \left(\frac{\delta_e}{F_{es}}\right)_{ss} M_{\delta_e} = M_{F_{es}} \qquad \frac{\text{deg}}{\text{lb-sec}^2} \tag{D.19}$$

For these configurations, no additional FCS dynamics (first order leads or lags) were added. The actuator dynamics were slightly faster and were

$$\frac{\delta_e(s)}{\delta_{e_c}(s)} = \frac{75.0^2}{s^2 + 2(0.67)(75.0)s + 75.0^2} \qquad \frac{\text{deg}}{\text{deg}} \tag{D.20}$$

All other dynamics were the same as for the previous eleven configurations.

D.2.3 Determination of Elevator Control Power and Gearing The transfer function gain, $M_{F_{es}}$, can be related to the published flight test parameters, using [MIL90, p.186]

$$\left.\frac{n}{F_{es}}\right|_{dB} = \left.\frac{M_{F_{es}}\left(\frac{n}{\alpha}\right)}{s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2}\right|_{s \to 0} = \frac{M_{F_{es}}\left(\frac{n}{\alpha}\right)}{\omega_{sp}^2} \qquad \frac{g}{\text{lb}} \tag{D.21}$$

Or upon rearranging with the appropriate conversion factor from radians to degrees

$$M_{F_{es}} = \frac{\omega_{sp}^2}{\left(\frac{n}{\alpha}\right)\left(\frac{F_{es}}{n}\right)} \frac{180}{\pi} \qquad \frac{\text{deg}}{\text{lb}-\text{sec}^2} \tag{D.22}$$

Values for ω_{sp}, and F_{es}/n were given for each configuration and the flight condition for all evaluations was $n/\alpha = 18.5\, g/\text{rad}$. These three variables allowed determination of $M_{F_{es}}$ for each configuration. The elevator control power was determined using

$$M_{\delta_e} = \frac{qSc}{I_{yy}} C_{M_{\delta_e}} \qquad \frac{1}{\text{rad}-\text{sec}^2} \tag{D.23}$$

From [HH70, p.185], $S = 234.8$ sq ft and $c = 6.72$ ft. From [Kno86b, p.5, 8] $I_{yy} = 21{,}000$ slug$-$ft^2 and $C_{M_{\delta_e}} = -0.494$ rad^{-1}. From [BCC74, p.44] $1/T_{\theta_2} = 1.25$ sec^{-1}. The complete flight conditions were not published and so q had to be related to the flight test parameters. The true airspeed in fps was determined using [MIL90, p.177]

$$\frac{n}{\alpha} = \frac{V_T}{g}\frac{1}{T_{\theta_2}} \qquad \frac{g}{\text{rad}} \tag{D.24}$$

Or upon rearranging

$$V_T = \frac{\left(\frac{n}{\alpha}\right)g}{\frac{1}{T_{\theta_2}}} = \frac{(18.5)(32.2)}{1.25} = 476.56 \quad \frac{\text{ft}}{\text{sec}} \tag{D.25}$$

$$\frac{V_T}{V_i} = \frac{1}{\sqrt{\frac{\rho}{\rho_0}}} = \frac{1}{\sqrt{\sigma}} = \frac{476.56}{250\left(\frac{6076}{3600}\right)} = 1.1279 \tag{D.26}$$

so $\sigma = 0.7860$ and $h = 8{,}000$ ft and

$$\rho = \rho_0 \sigma = (0.0023769)(0.7860) = 0.001869 \quad \frac{\text{slugs}}{\text{ft}^3} \tag{D.27}$$

The dynamics pressure is

$$q = \frac{\rho V_T^2}{2} = \frac{(0.001869)(476.56)^2}{2} = 212.23 \quad \frac{\text{lb}}{\text{ft}^2} \tag{D.28}$$

and from Eqn D.23

$$M_{\delta_e} = \frac{(212.23)(234.8)(6.72)}{21{,}000}(-0.494) = -7.8774 \quad \frac{1}{\text{rad}-\text{sec}^2} \tag{D.29}$$

Finally

$$\left(\frac{\delta_e}{F_{es}}\right)_{ss} = \frac{M_{F_{es}}}{M_{\delta_e}} \quad \frac{\text{deg}}{\text{lb}} \tag{D.30}$$

The data required to model the 1974 Calspan configurations are listed in Eqn D.29 and Table D.1.

Table D.1. Calspan Configurations [BCC74, p.44][1]

Calspan Configurations: $1/T_{\theta_2} = 1.25\ \sec^{-1}$, $U_0 = 476.56$ fps, $x_a = 6.53$ ft					
Config	$(\delta_e/F_{es})_{ss}$ (deg/lb)	$[\zeta_{sp}, \omega_{sp}]$ (-, rad/sec)	$[\zeta_3, \omega_3]$ (-, rad/sec)	$\left(\frac{1}{\tau_1}\right)/\left(\frac{1}{\tau_2}\right)$ (—)	F_{es}/n (lb/g)
1B	-0.3281	[0.70,2.2]	[0.75,63]	(0.5)/(0.2)	5.8
2D	-1.2248	[0.72,4.5]	[0.75,63]	—	6.5
2A	-1.4217	[0.72,4.5]	[0.75,63]	(0.5)/(0.2)	5.6
11	-0.3568	[1.0,3.3]	[0.67,75]	—	12.0
1D	-0.3281	[0.70,2.2]	[0.75,63]	—	5.8
4A	-1.3052	[0.29,4.5]	[0.75,63]	—	6.1
4D	-0.7173	[0.29,4.5]	[0.75,63]	(0.0)/(0.5)	11.1
5A	-1.2962	[0.18,4.7]	[0.75,63]	—	6.7
10	-0.3355	[1.1,2.3]	[0.67,75]	—	6.2
9	-0.2536	[1.7,2.3]	[0.67,75]	—	8.2
5D	-0.9758	[0.18,4.7]	[0.75,63]	(0.0)/(0.5)	8.9
2J	-1.4743	[0.72,4.5]	[0.75,63]	(0.0)/(2.0)	5.4
5E	-1.1427	[0.18,4.7]	[0.75,63]	(0.0)/(2.0)	7.6
1E	-0.2187	[0.70,2.2]	[0.75,63]	(0.0)/(0.2)	8.7

D.3 Frequency Responses and Time Histories for Calspan Configurations

The following figures are the θ/F_{es}, γ/F_{es} frequency responses and the time histories to a 10 lb boxcar input for the Calspan configurations.

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[1]Values for U_0 and $(\delta_e/F_{es})_{ss}$ were computed, all other data are from [BCC74, p.44] except for x_a, which is from [Hef72, p.22].

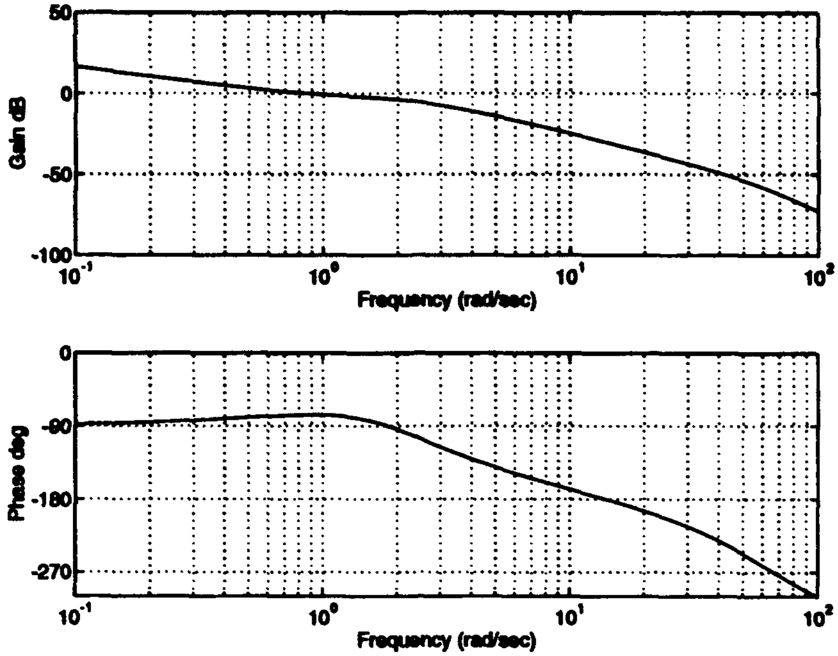

Figure D.3. Calspan Configuration 1B θ/F_{es} Frequency Response

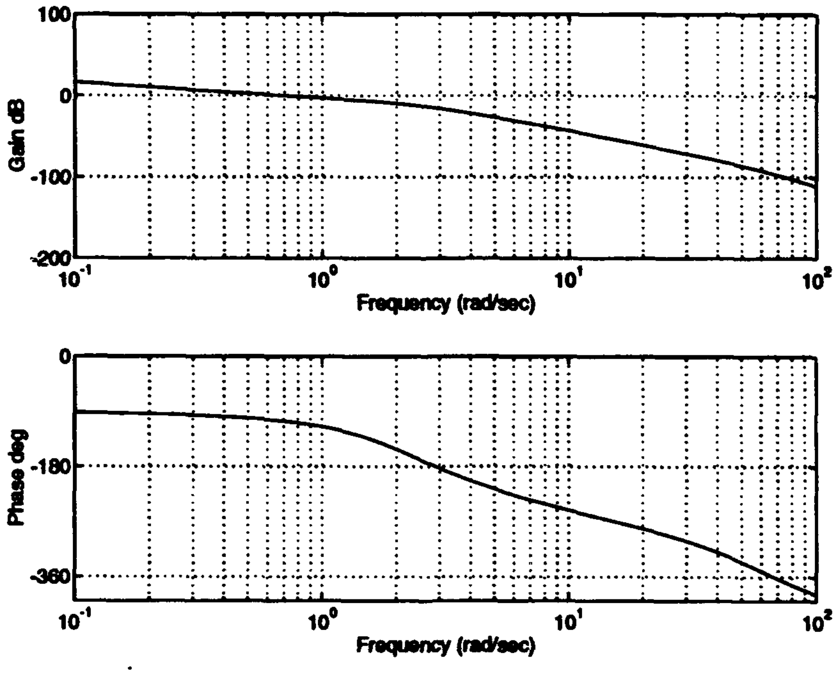

Figure D.4. Calspan Configuration 1B γ/F_{es} Frequency Response

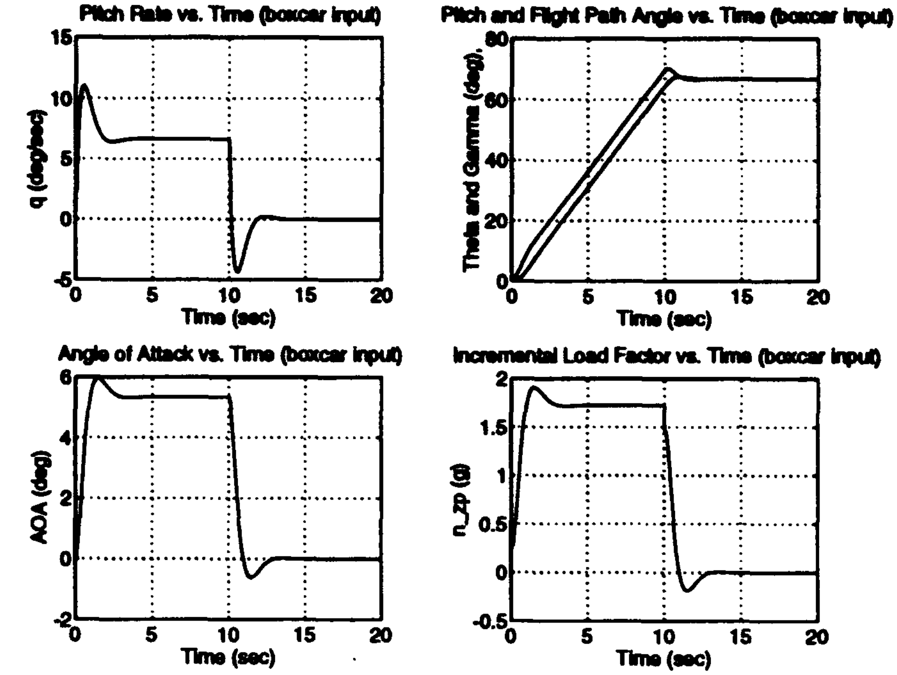

Figure D.5. Calspan Configuration 1B Time Responses

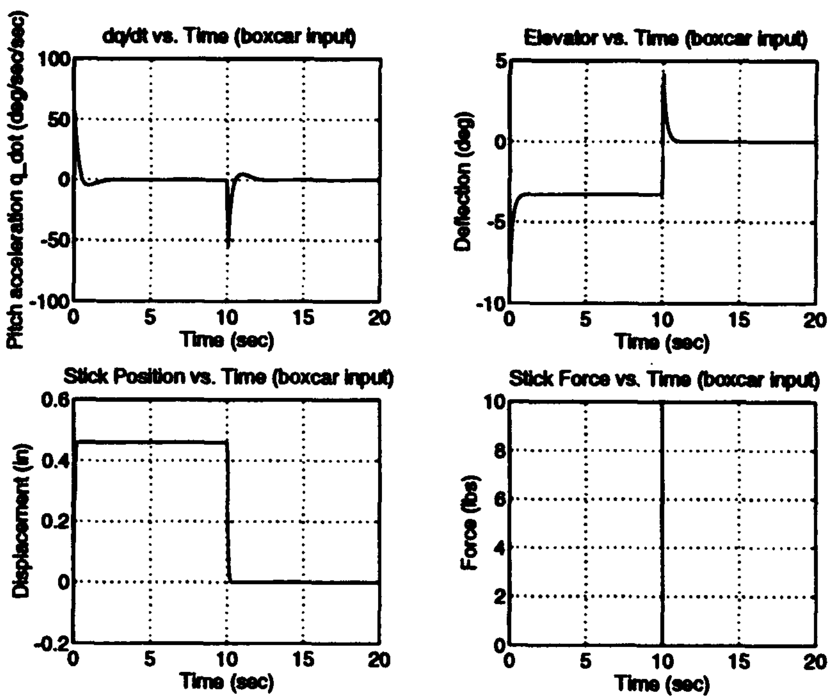

Figure D.6. Calspan Configuration 1B Time Responses

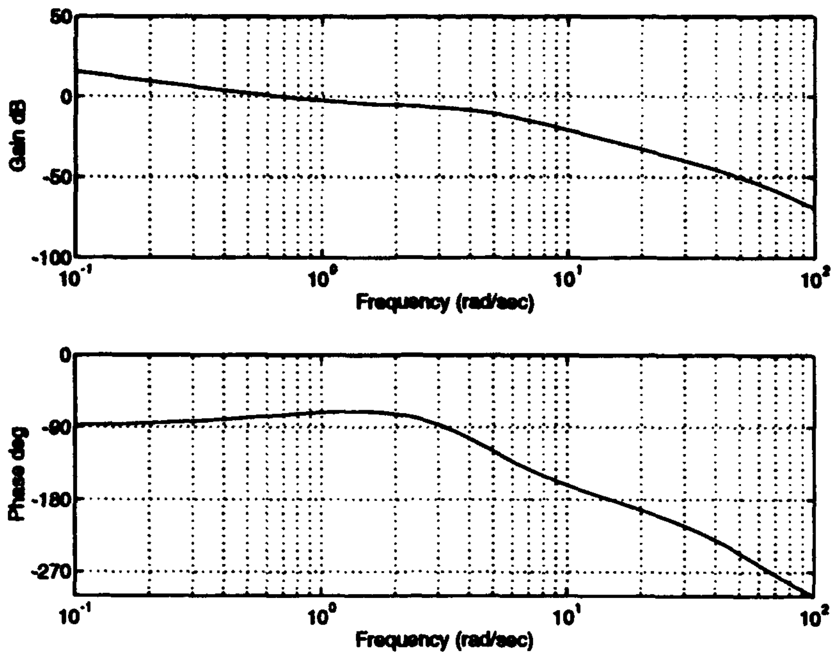

Figure D.7. Calspan Configuration 2D θ/F_{es} Frequency Response

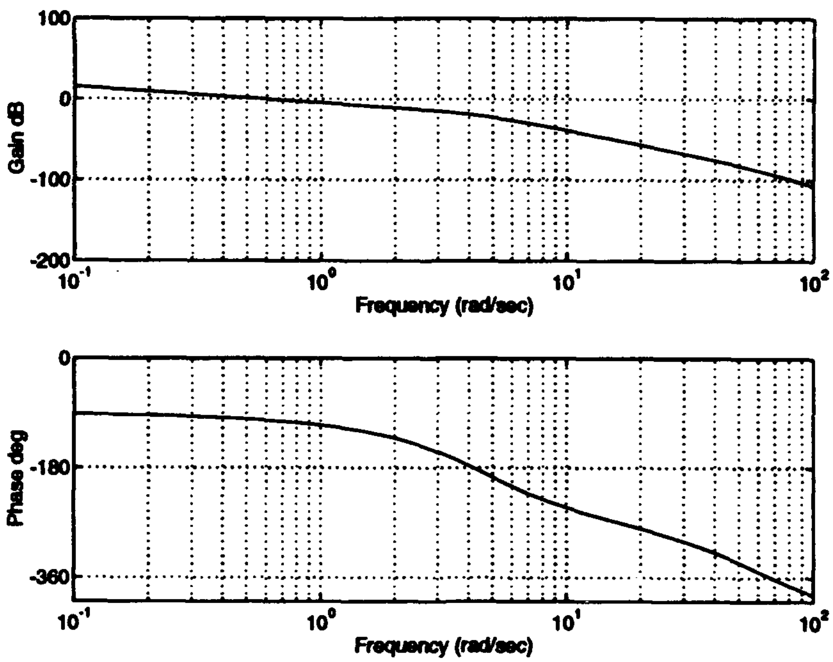

Figure D.8. Calspan Configuration 2D γ/F_{es} Frequency Response

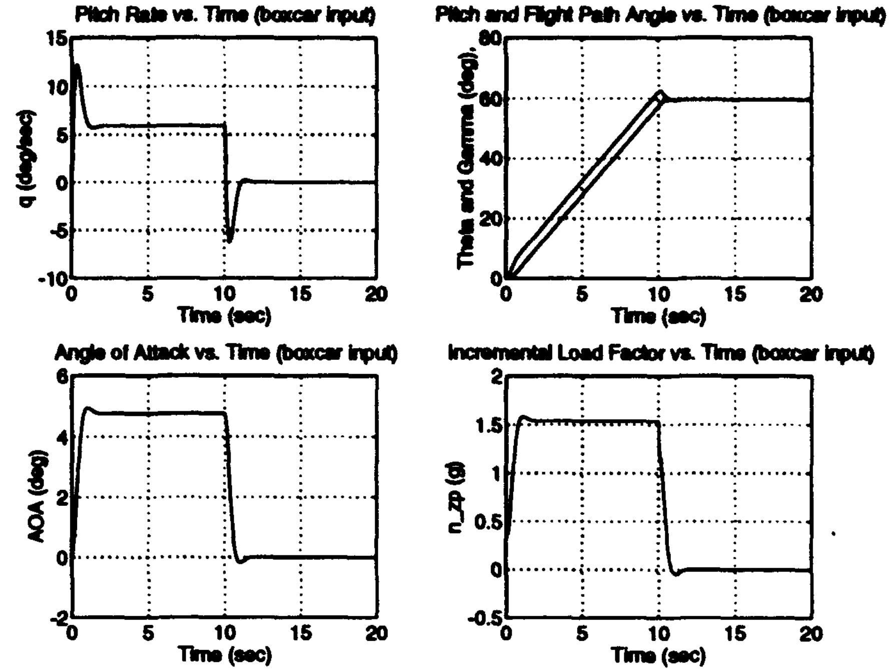

Figure D.9. Calspan Configuration 2D Time Responses

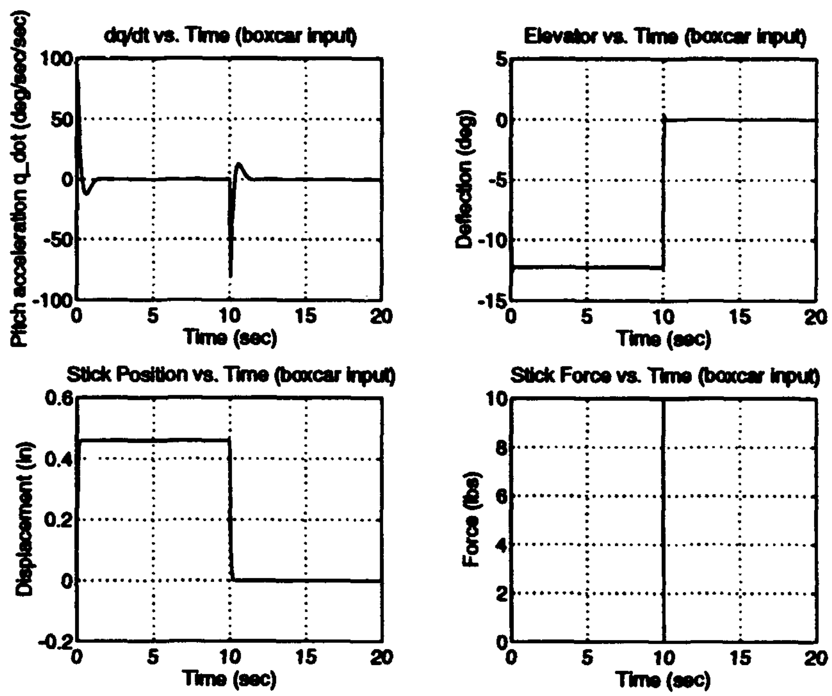

Figure D.10. Calspan Configuration 2D Time Responses

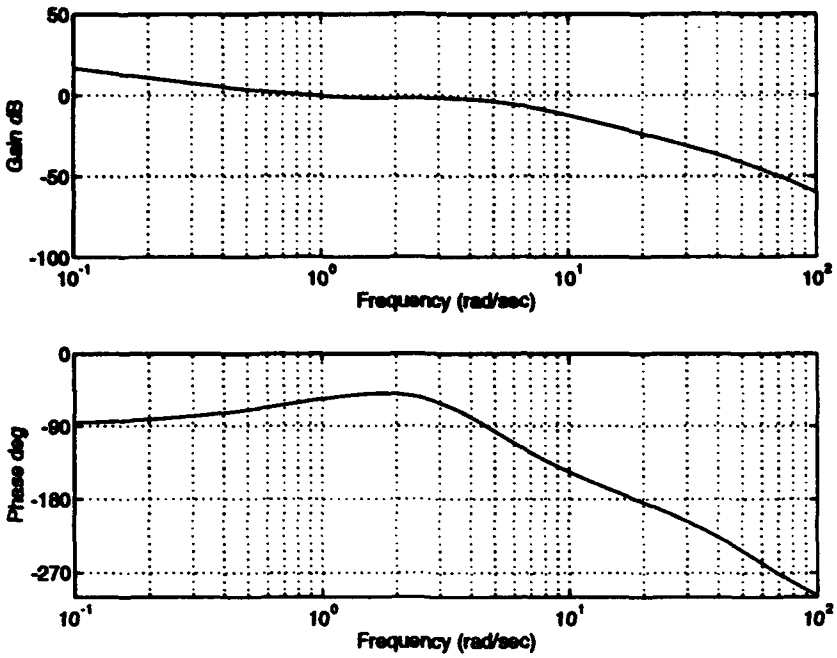

Figure D.11. Calspan Configuration 2A θ/F_{es} Frequency Response

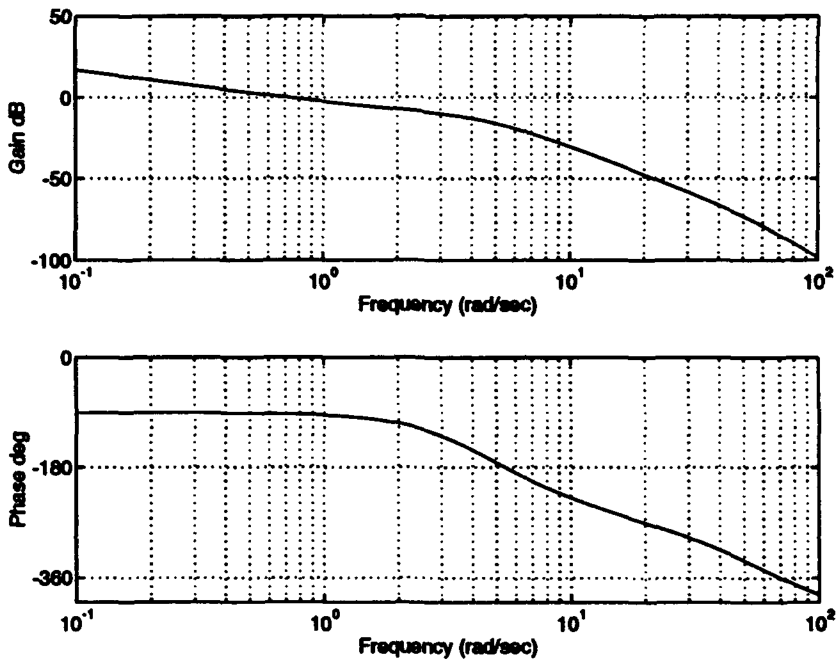

Figure D.12. Calspan Configuration 2A γ/F_{es} Frequency Response

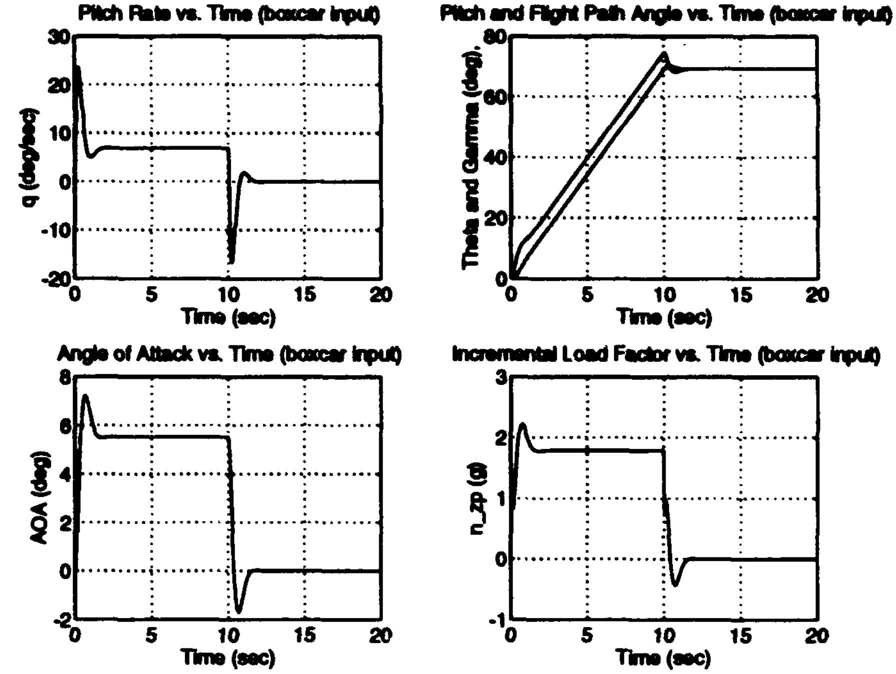

Figure D.13. Calspan Configuration 2A Time Responses

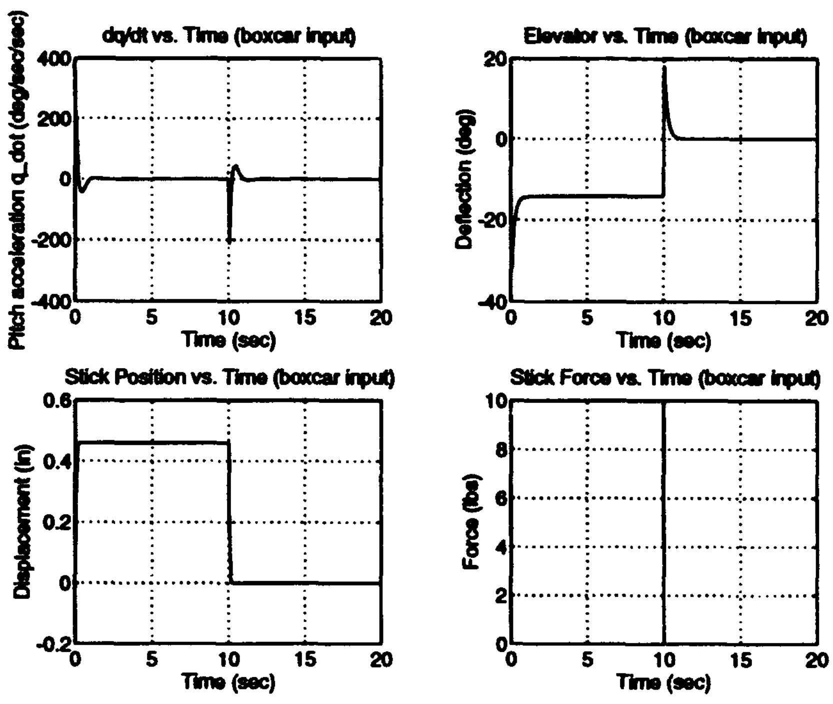

Figure D.14. Calspan Configuration 2A Time Responses

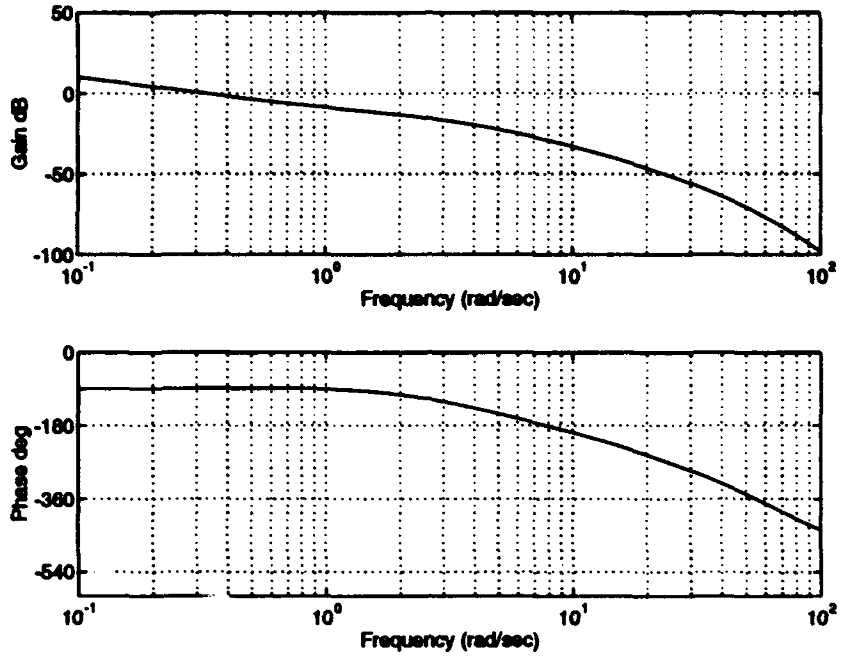

Figure D.15. Calspan Configuration 11 θ/F_{es} Frequency Response

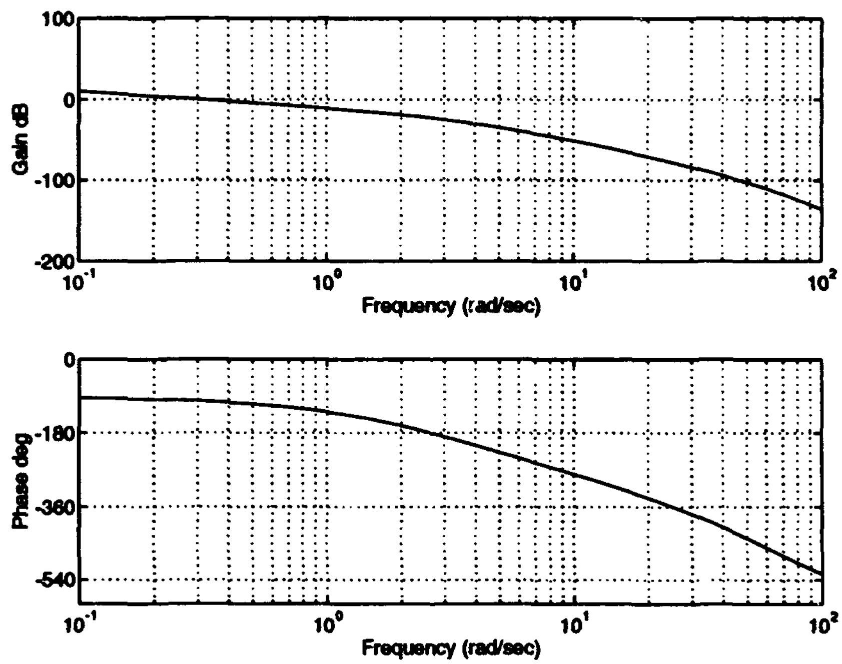

Figure D.16. Calspan Configuration 11 γ/F_{es} Frequency Response

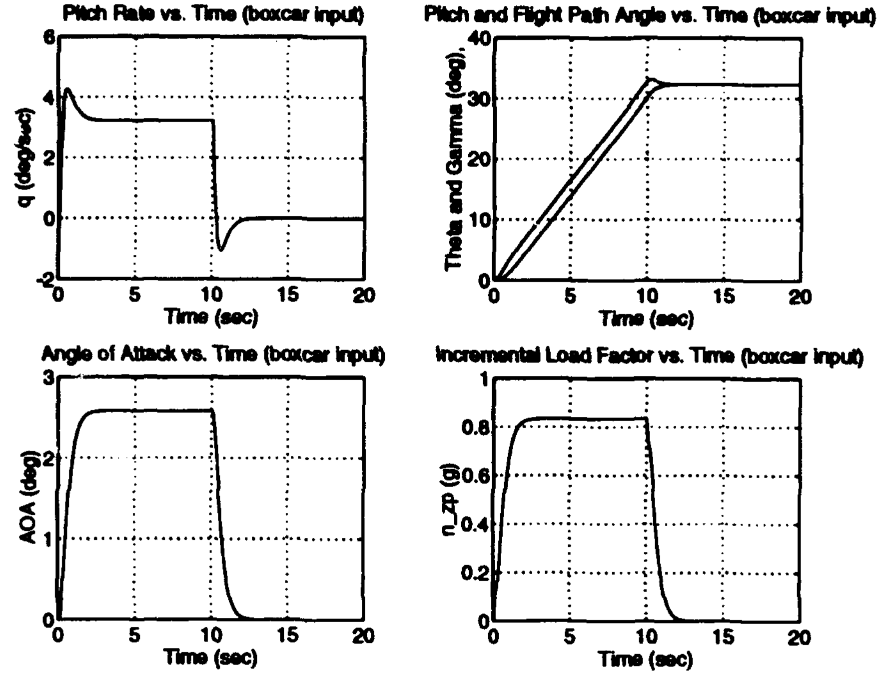

Figure D.17. Calspan Configuration 11 Time Responses

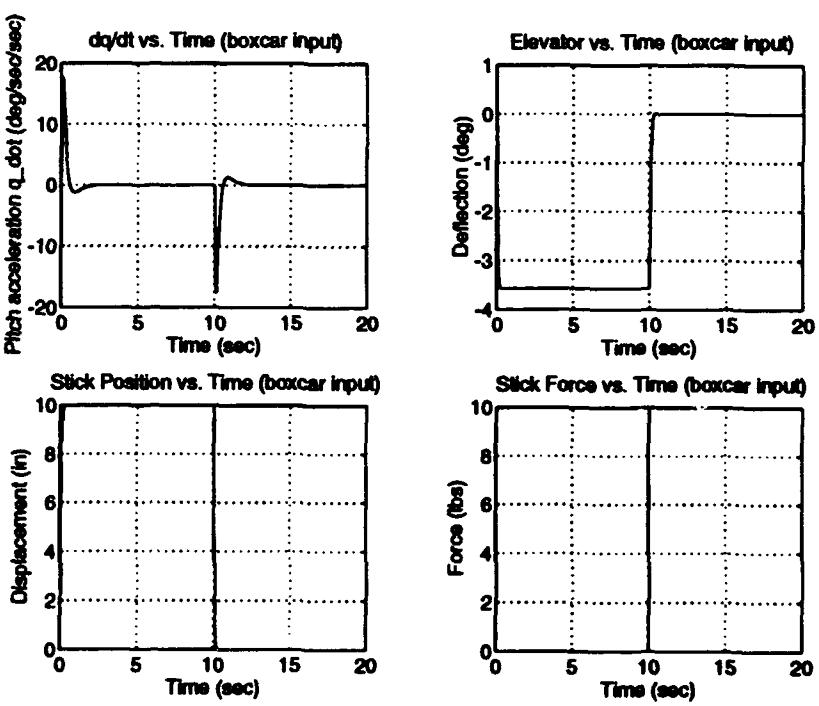

Figure D.18. Calspan Configuration 11 Time Responses

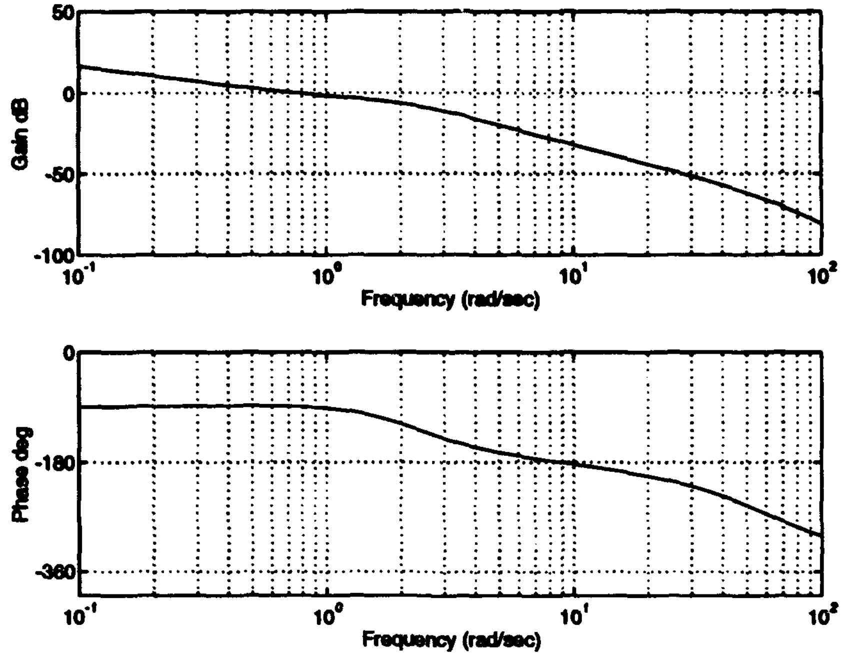

Figure D.19. Calspan Configuration 1D θ/F_{es} Frequency Response

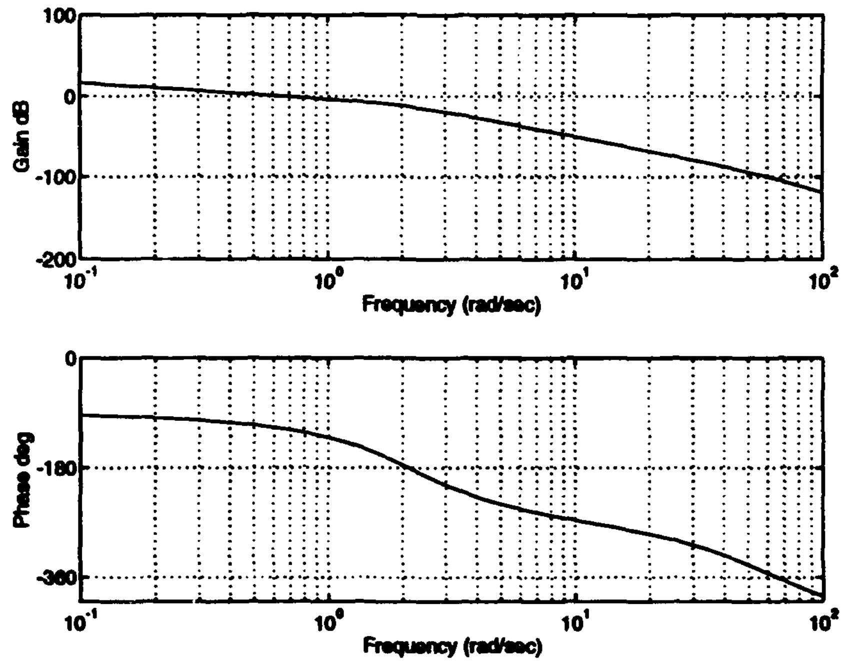

Figure D.20. Calspan Configuration 1D γ/F_{es} Frequency Response

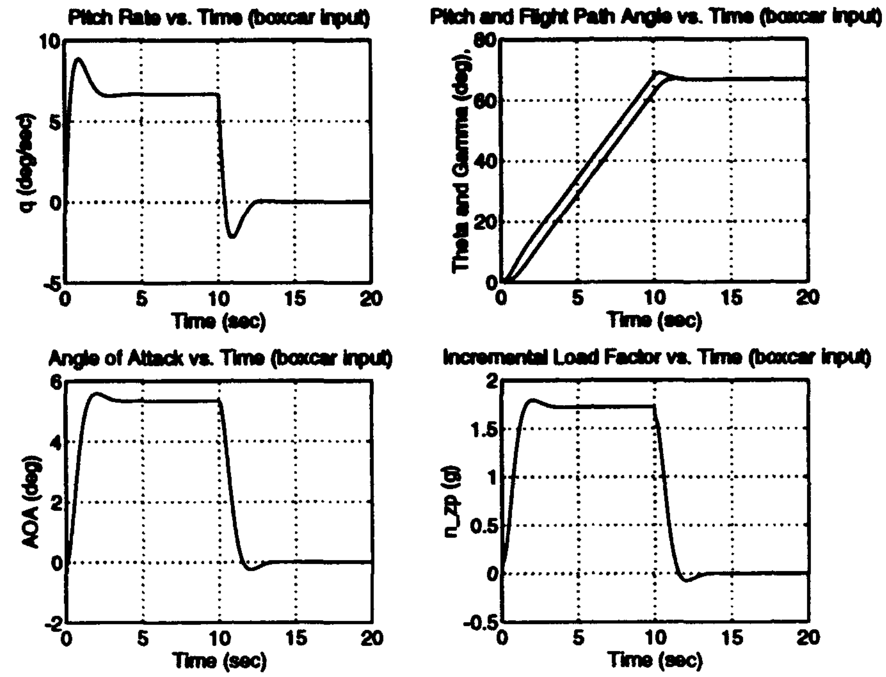

Figure D.21. Calspan Configuration 1D Time Responses

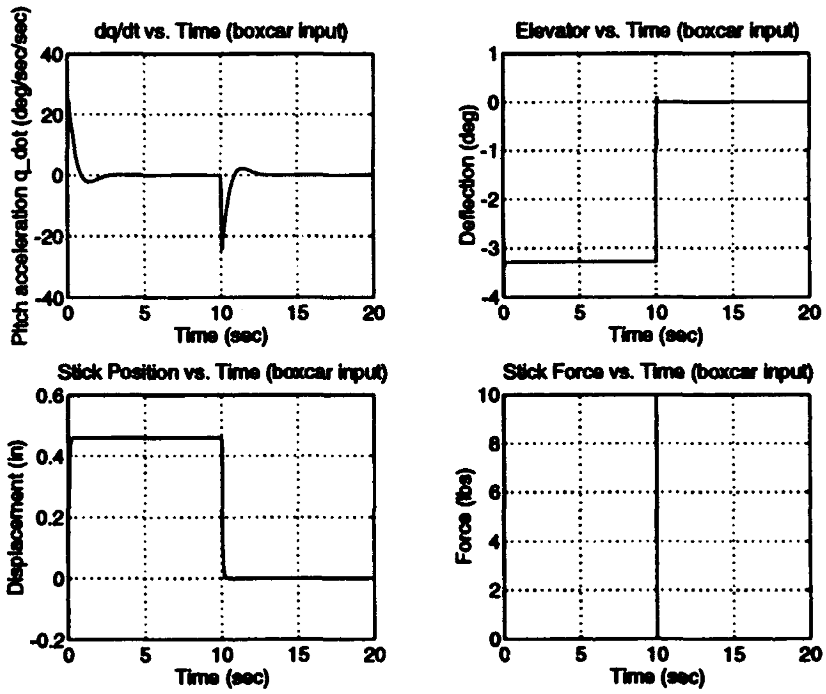

Figure D.22. Calspan Configuration 1D Time Responses

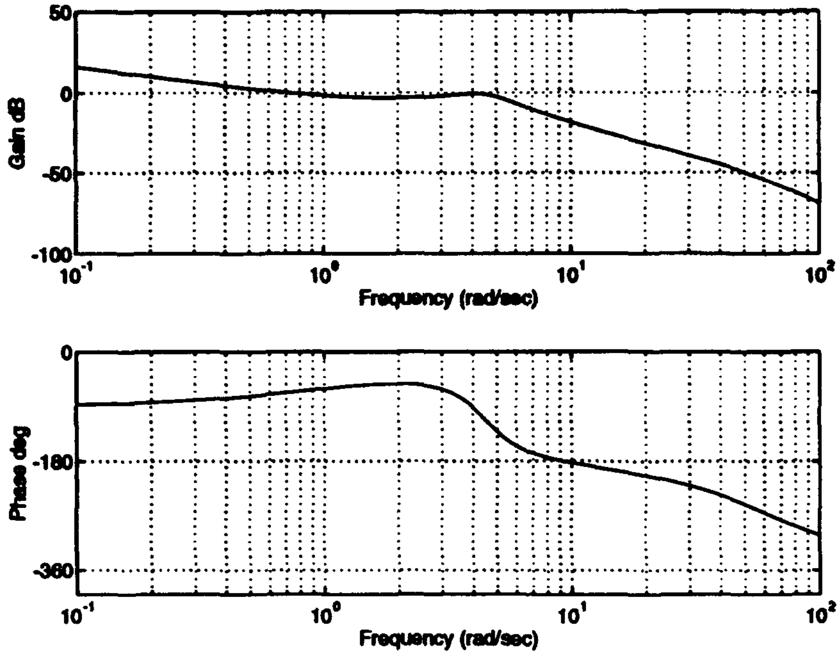

Figure D.23. Calspan Configuration 4A θ/F_{es} Frequency Response

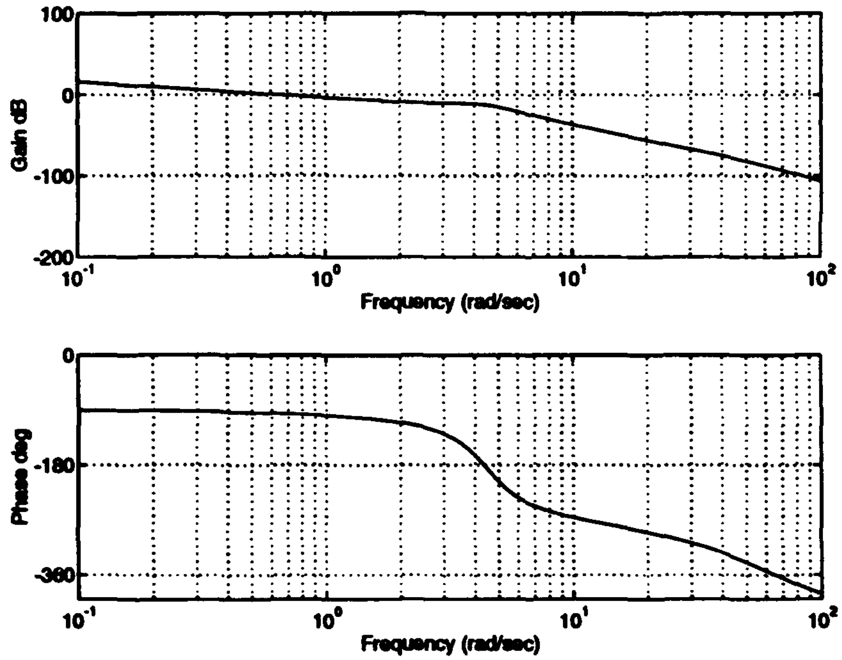

Figure D.24. Calspan Configuration 4A γ/F_{es} Frequency Response

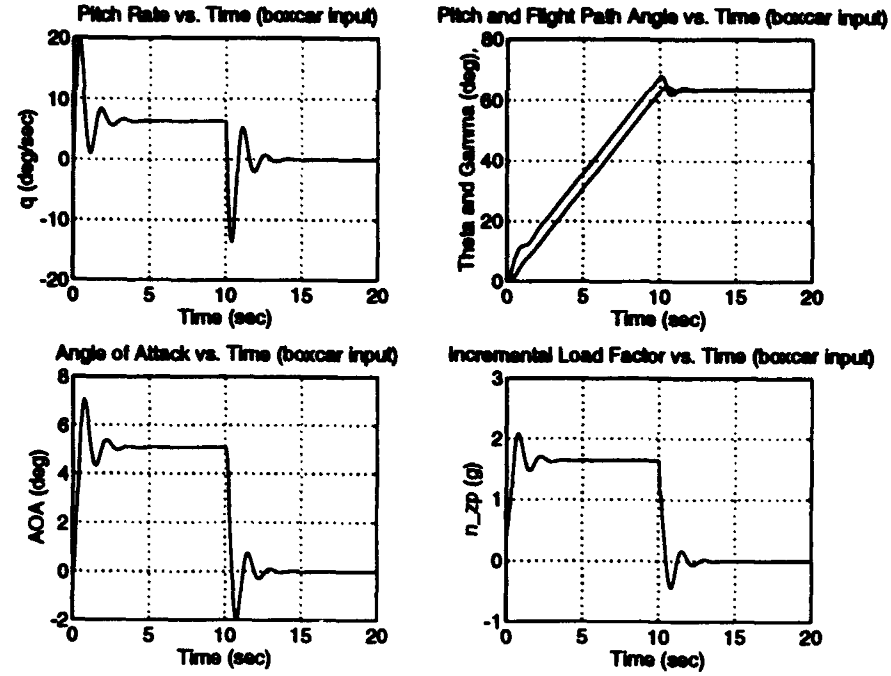

Figure D.25. Calspan Configuration 4A Time Responses

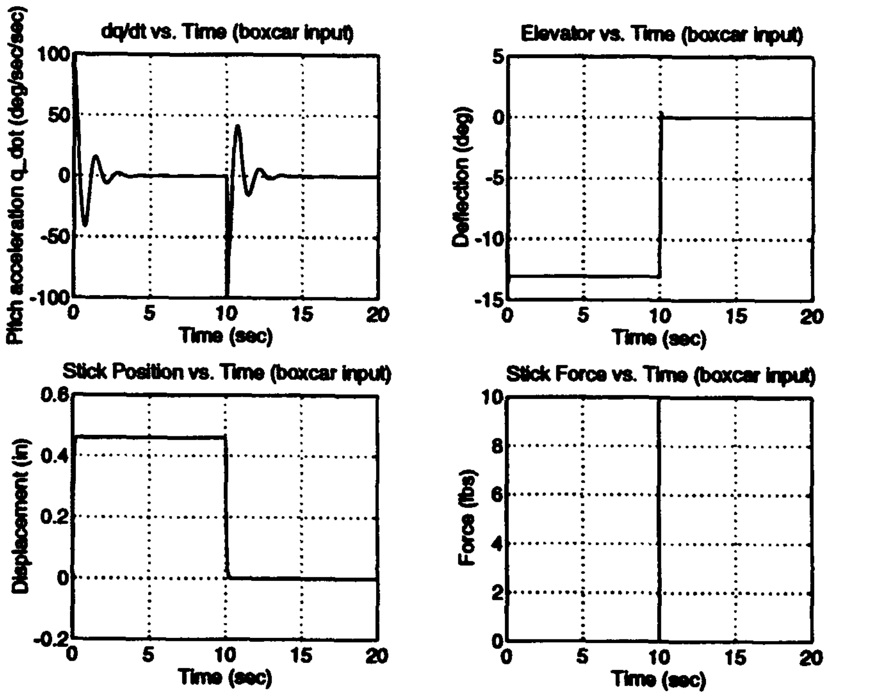

Figure D.26. Calspan Configuration 4A Time Responses

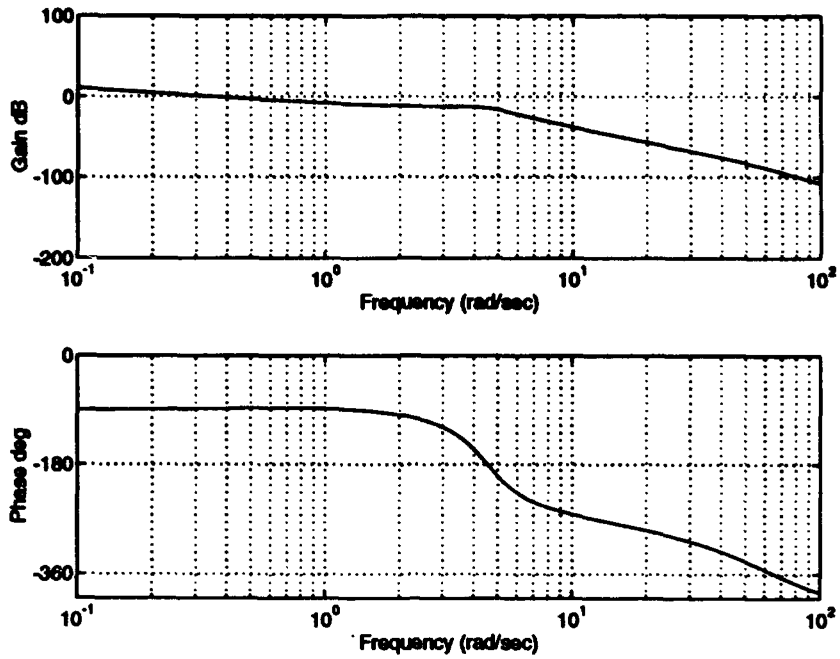

Figure D.27. Calspan Configuration 4D θ/F_{es} Frequency Response

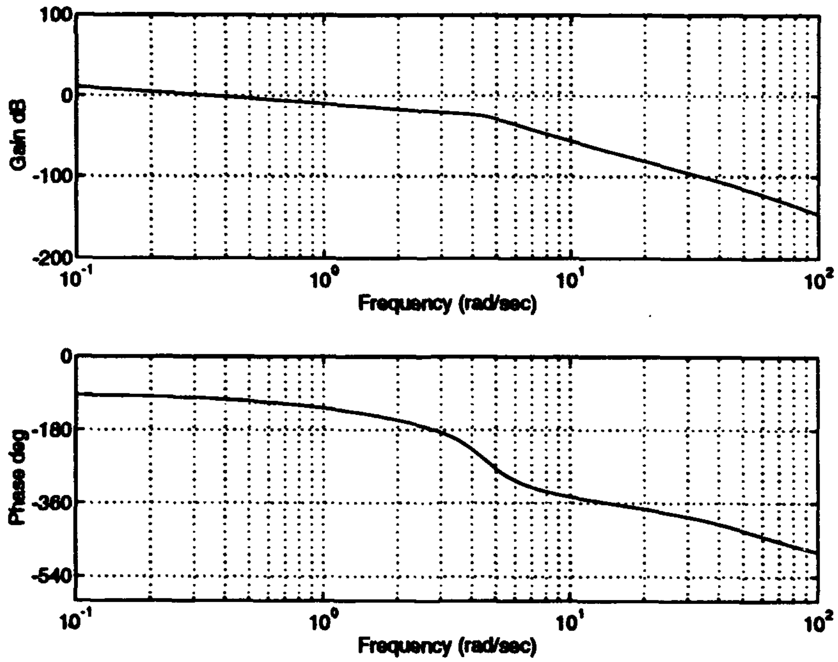

Figure D.28. Calspan Configuration 4D γ/F_{es} Frequency Response

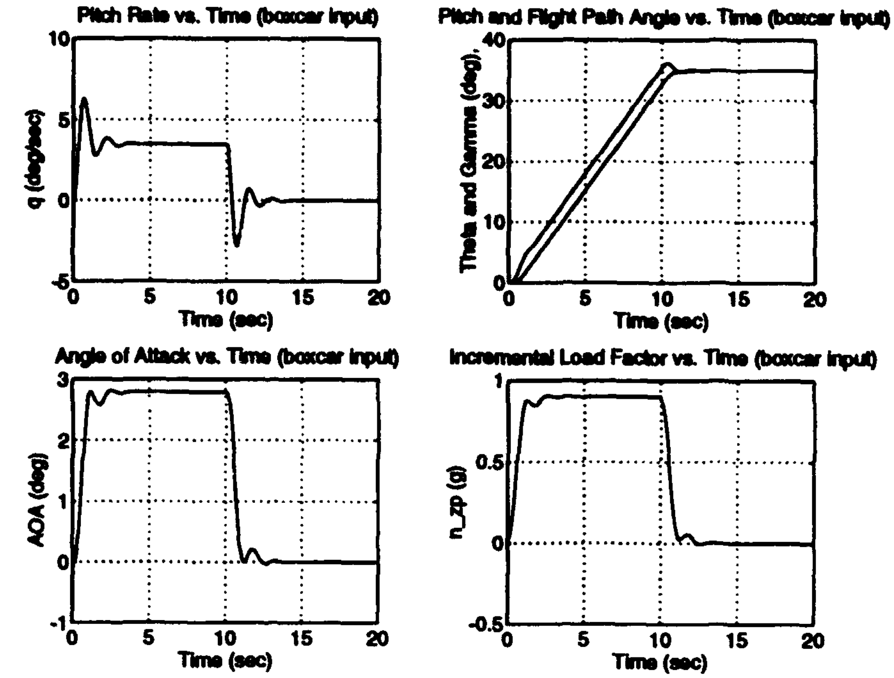

Figure D.29. Calspan Configuration 4D Time Responses

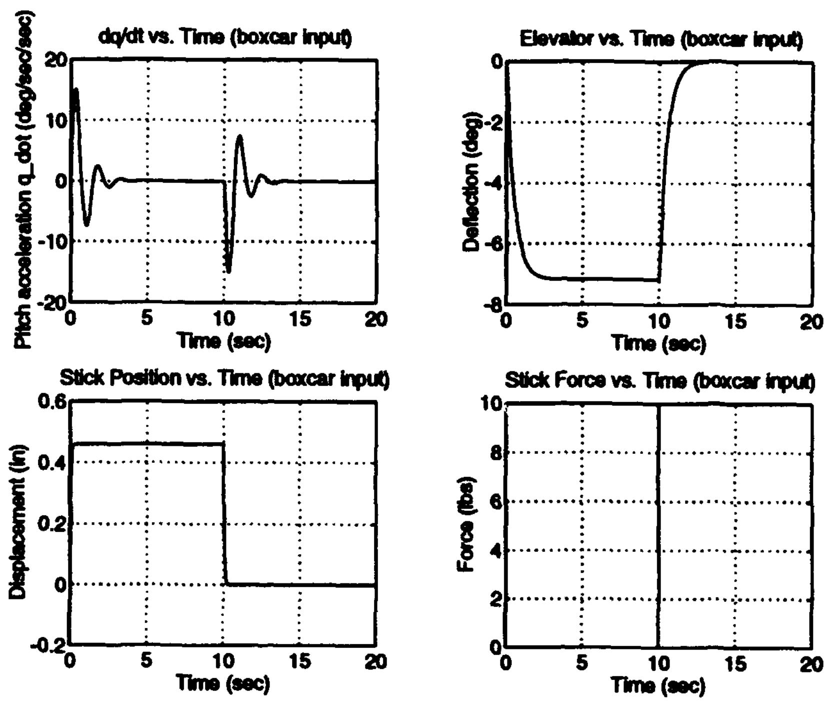

Figure D.30. Calspan Configuration 4D Time Responses

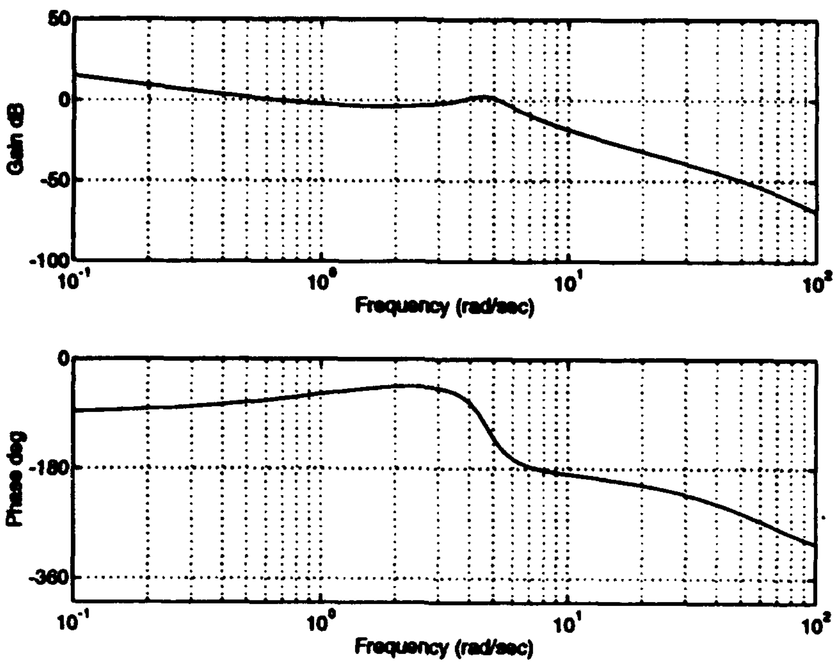

Figure D.31. Calspan Configuration 5A θ/F_{es} Frequency Response

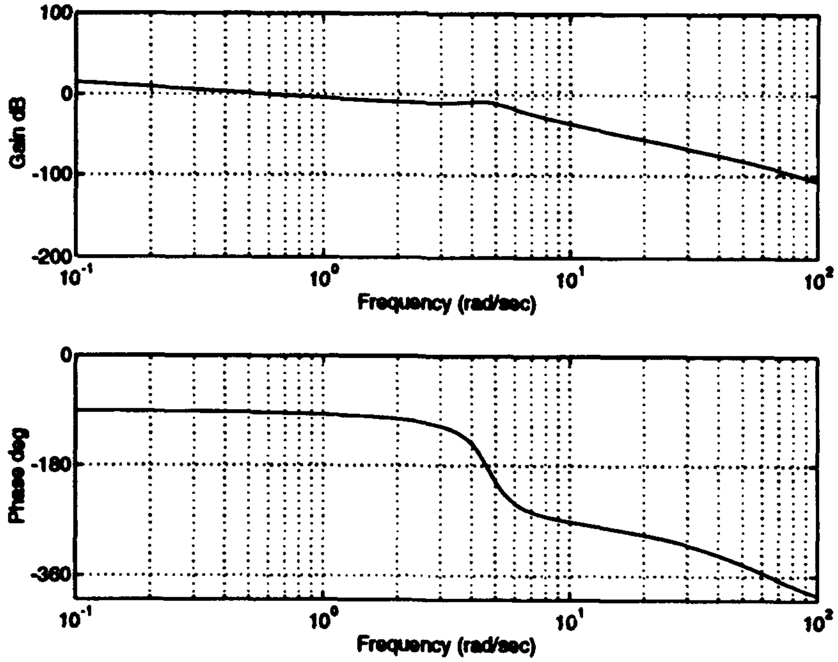

Figure D.32. Calspan Configuration 5A γ/F_{es} Frequency Response

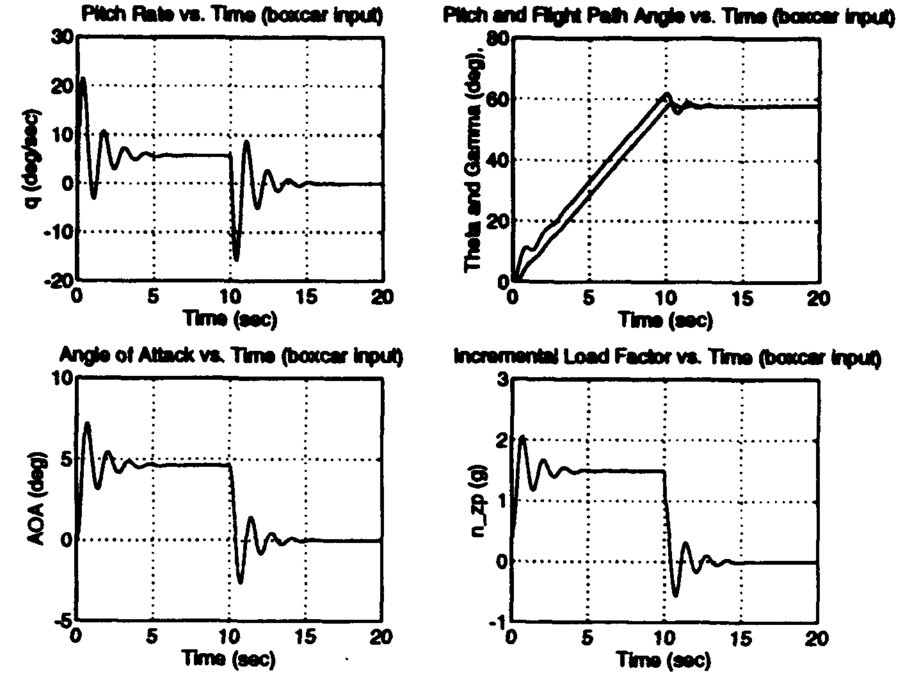

Figure D.33. Calspan Configuration 5A Time Responses

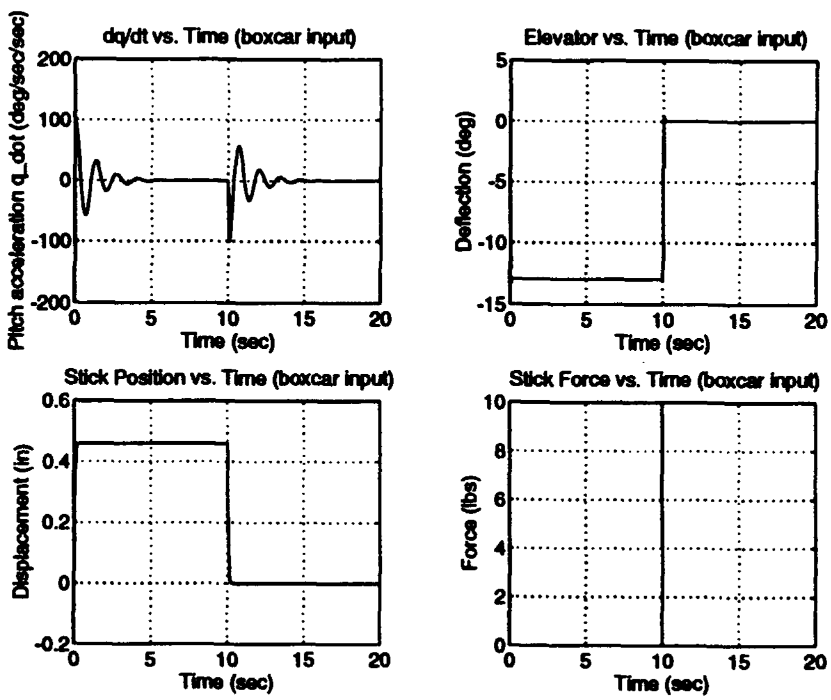

Figure D.34. Calspan Configuration 5A Time Responses

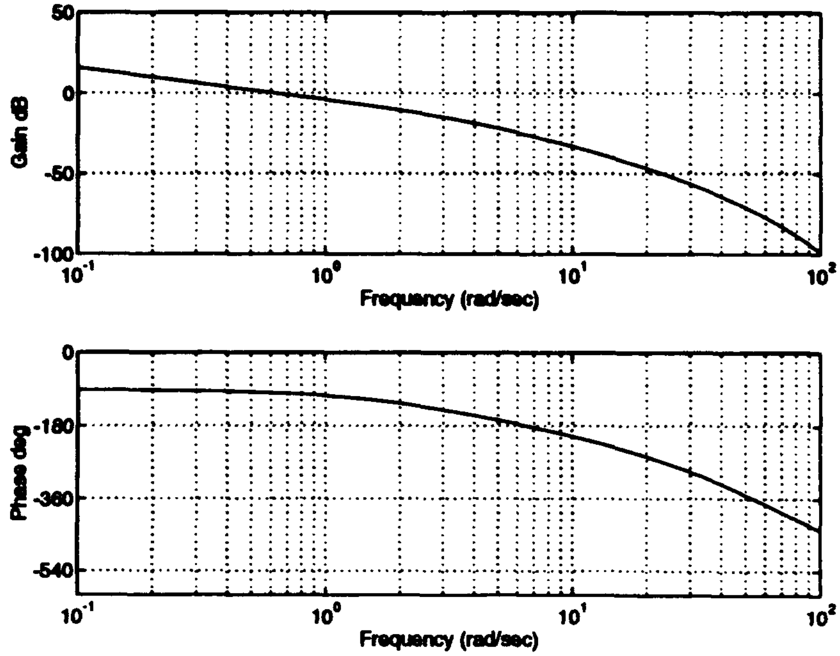

Figure D.35. Calspan Configuration 10 θ/F_{es} Frequency Response

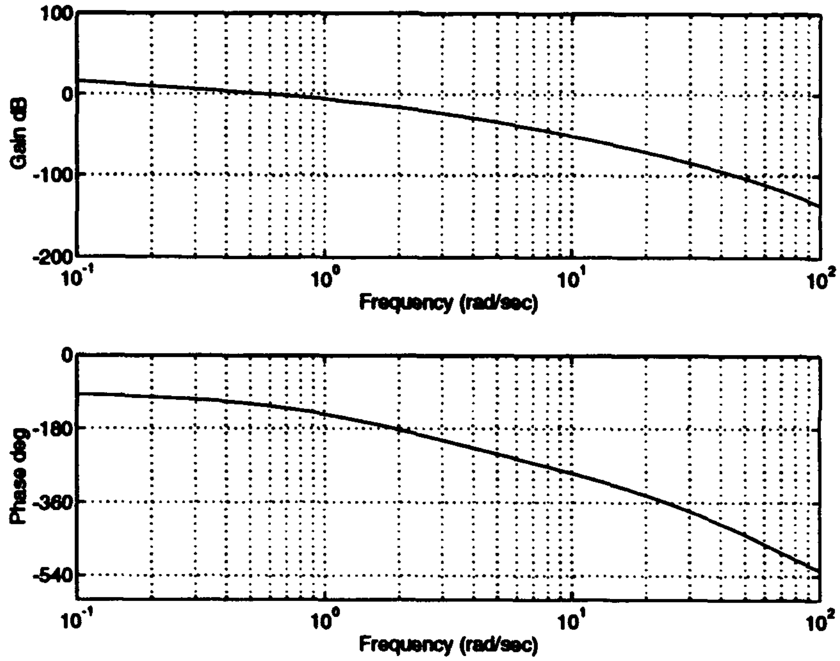

Figure D.36. Calspan Configuration 10 γ/F_{es} Frequency Response

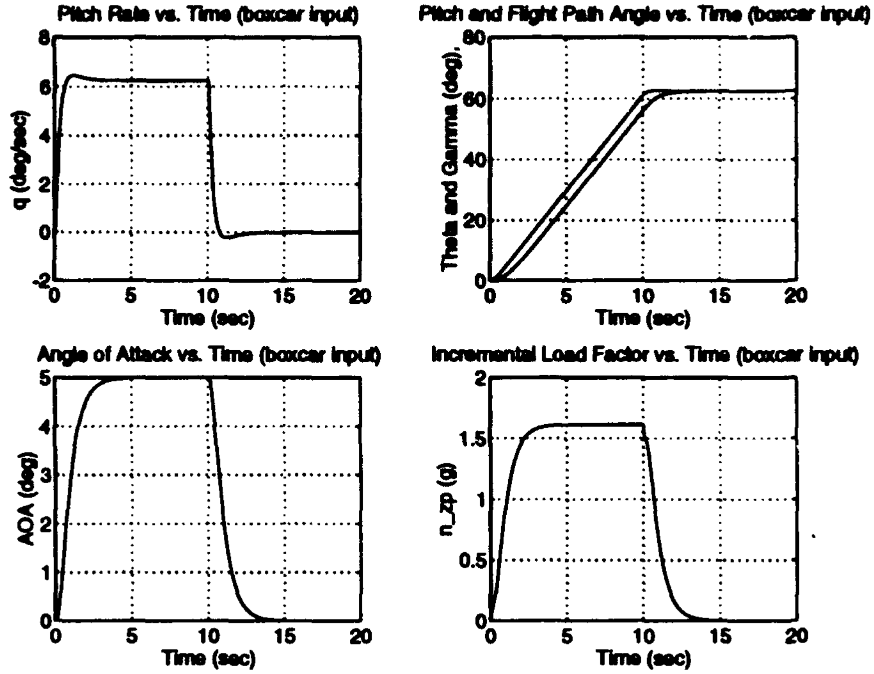

Figure D.37. Calspan Configuration 10 Time Responses

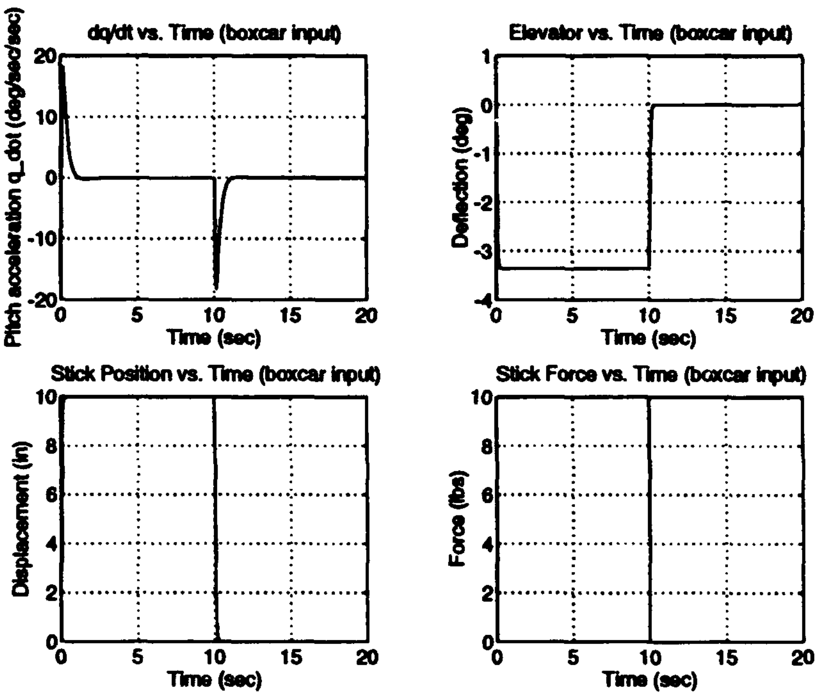

Figure D.38. Calspan Configuration 10 Time Responses

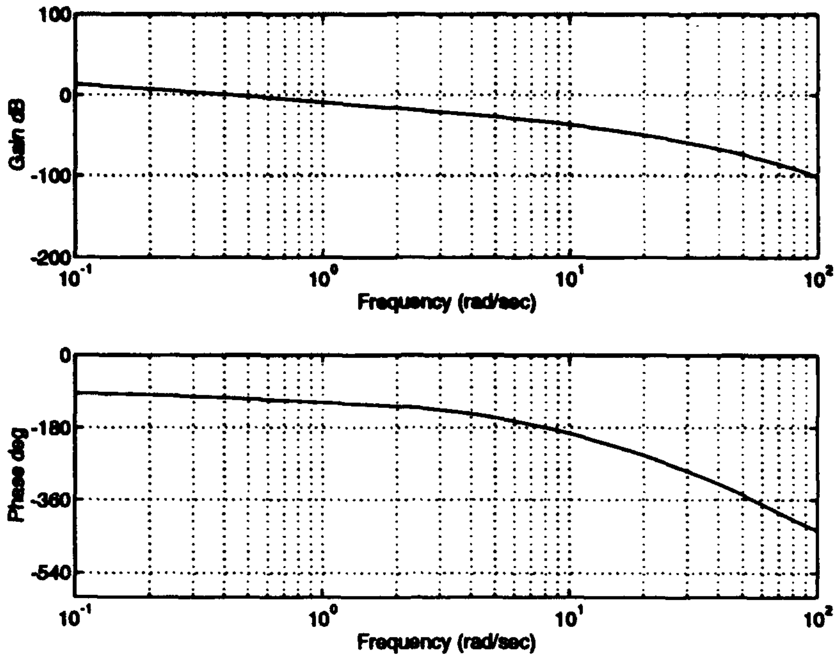

Figure D.39. Calspan Configuration 9 θ/F_{es} Frequency Response

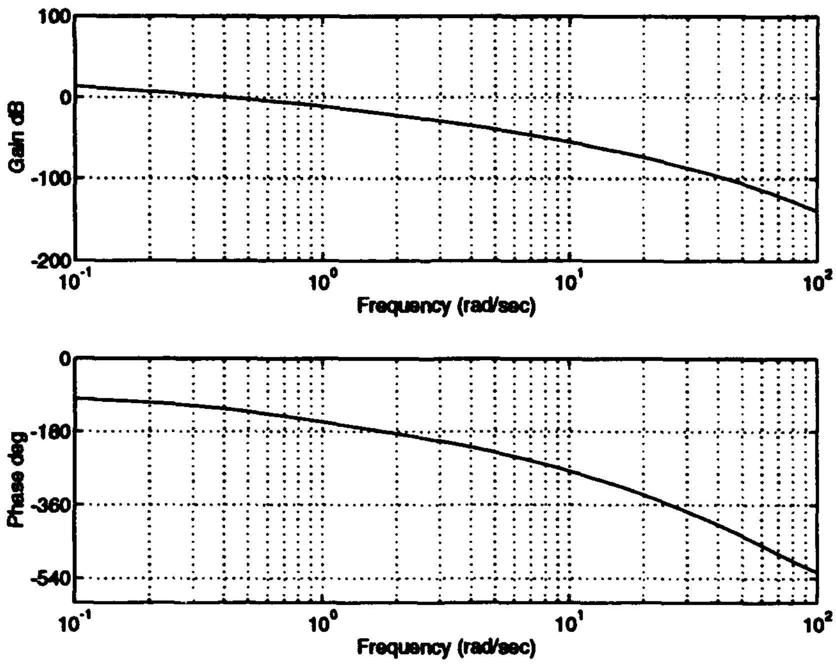

Figure D.40. Calspan Configuration 9 γ/F_{es} Frequency Response

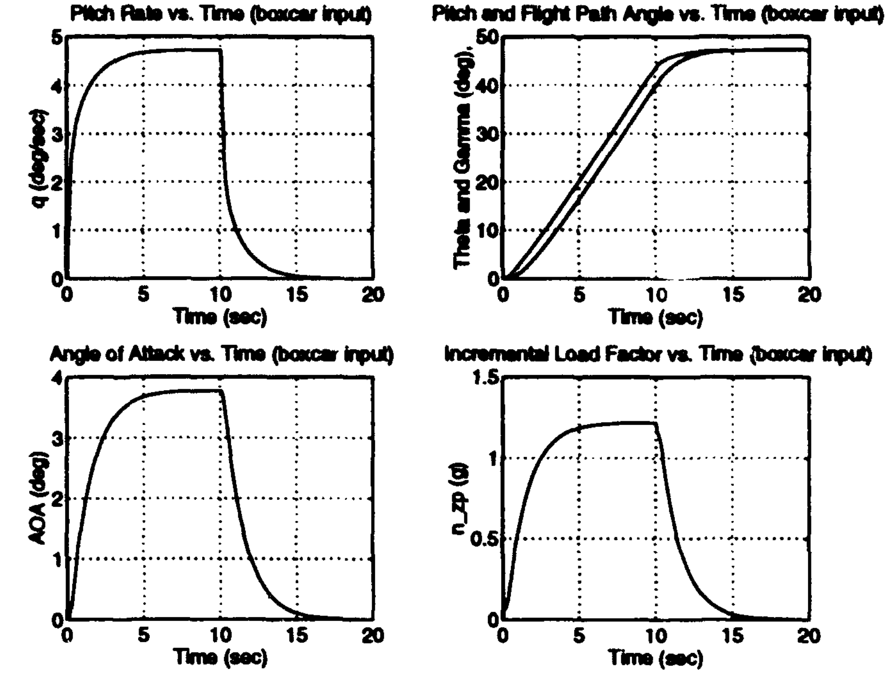

Figure D.41. Calspan Configuration 9 Time Responses

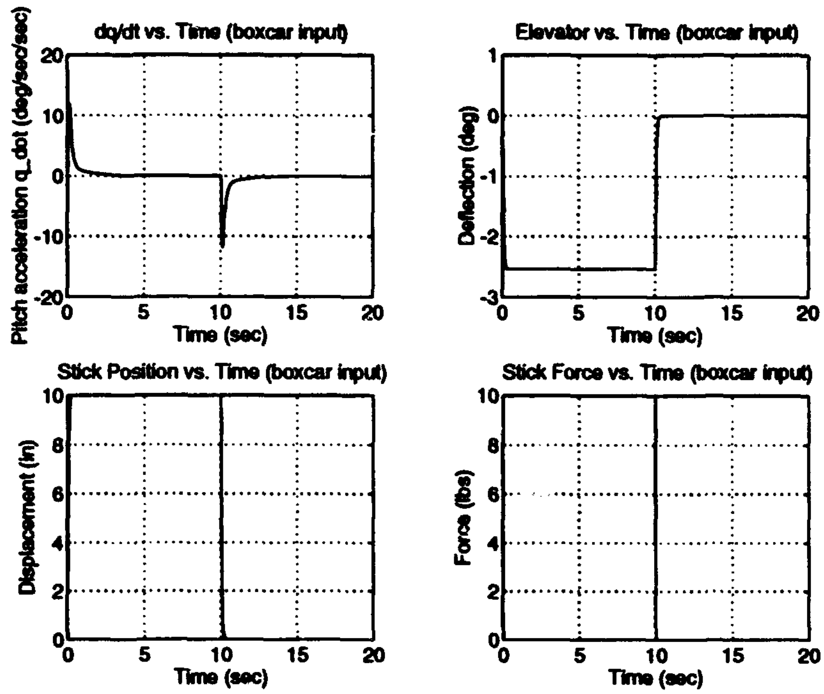

Figure D.42. Calspan Configuration 9 Time Responses

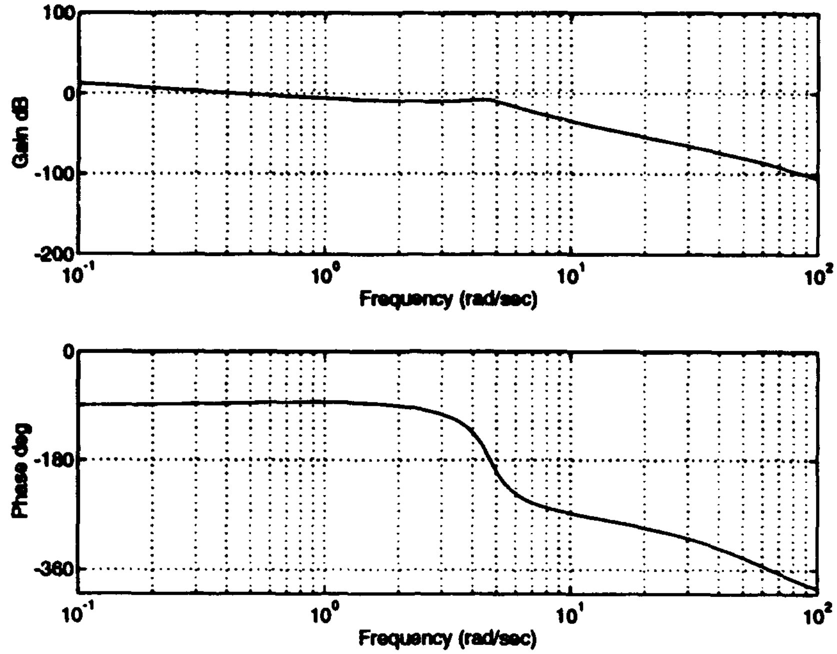

Figure D.43. Calspan Configuration 5D θ/F_{es} Frequency Response

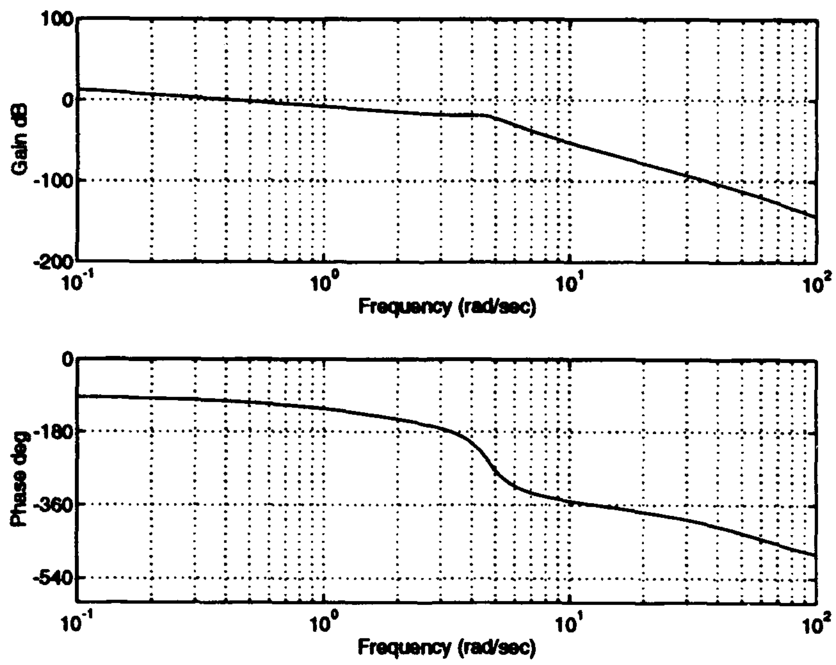

Figure D.44. Calspan Configuration 5D γ/F_{es} Frequency Response

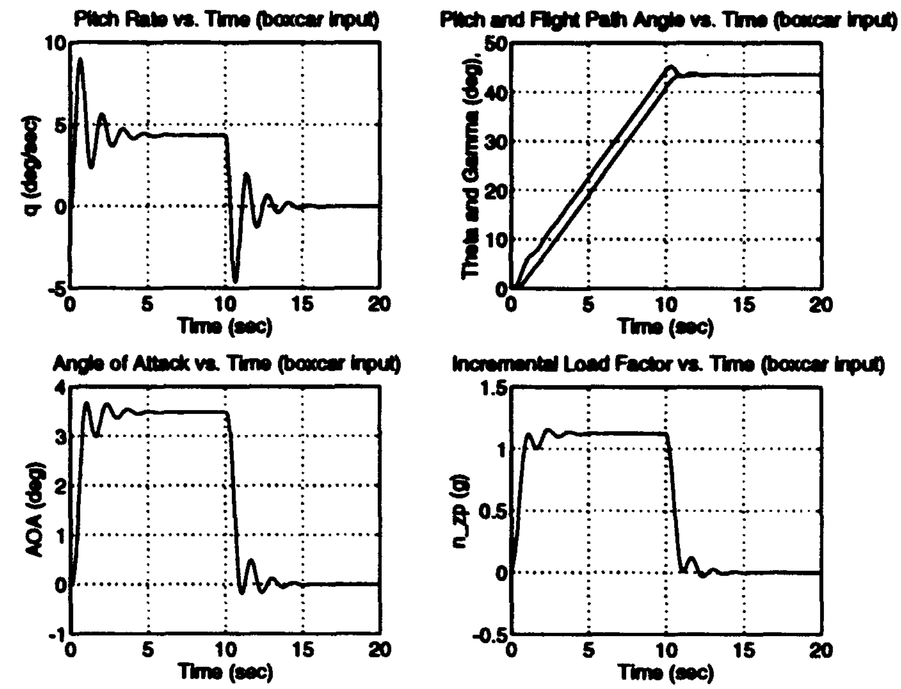

Figure D.45. Calspan Configuration 5D Time Responses

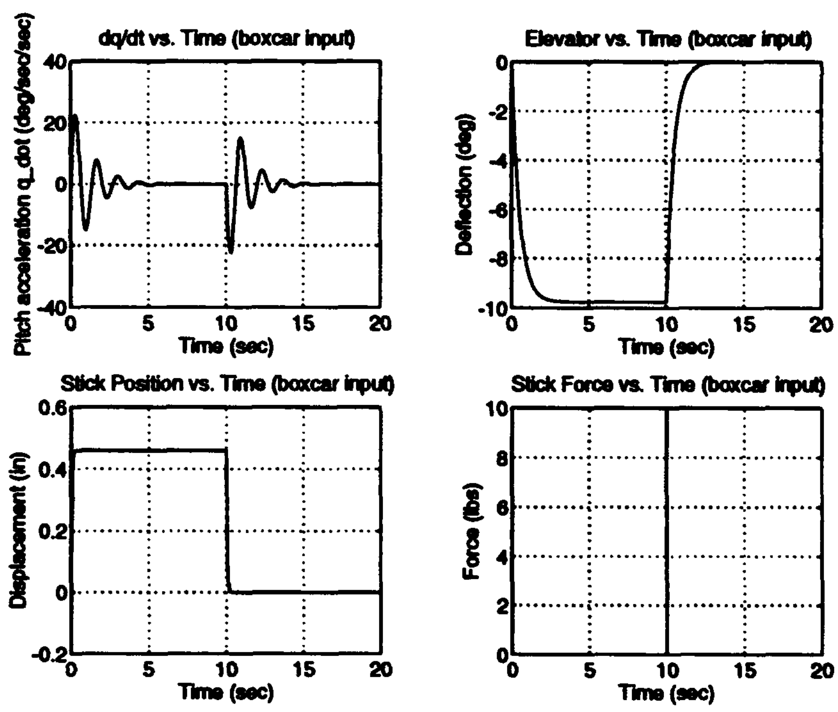

Figure D.46. Calspan Configuration 5D Time Responses

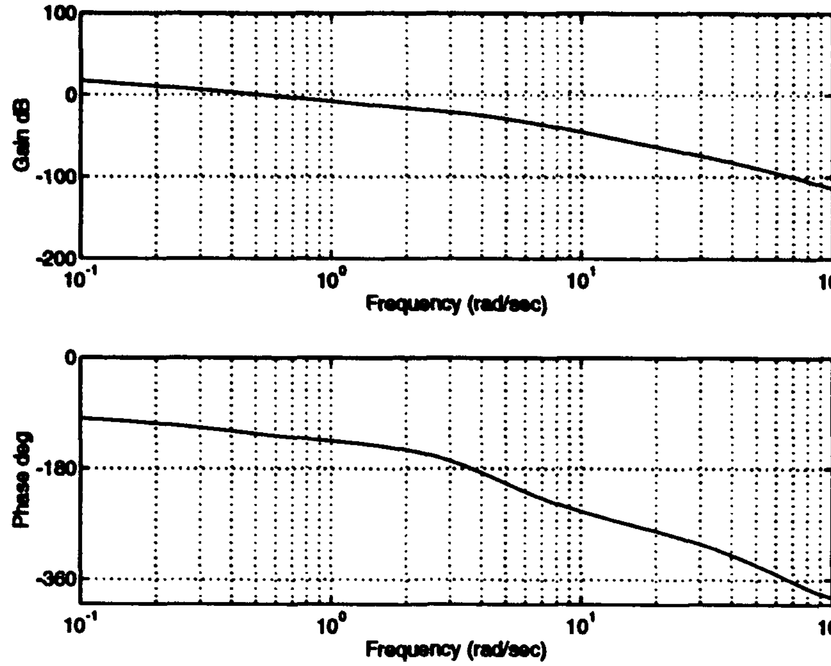

Figure D.47. Calspan Configuration 2J θ/F_{es} Frequency Response

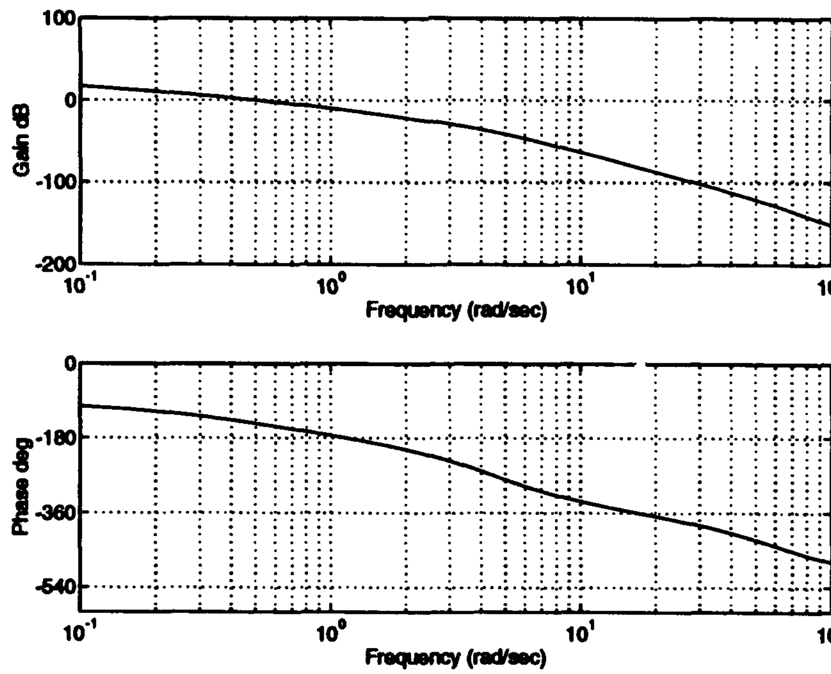

Figure D.48. Calspan Configuration 2J γ/F_{es} Frequency Response

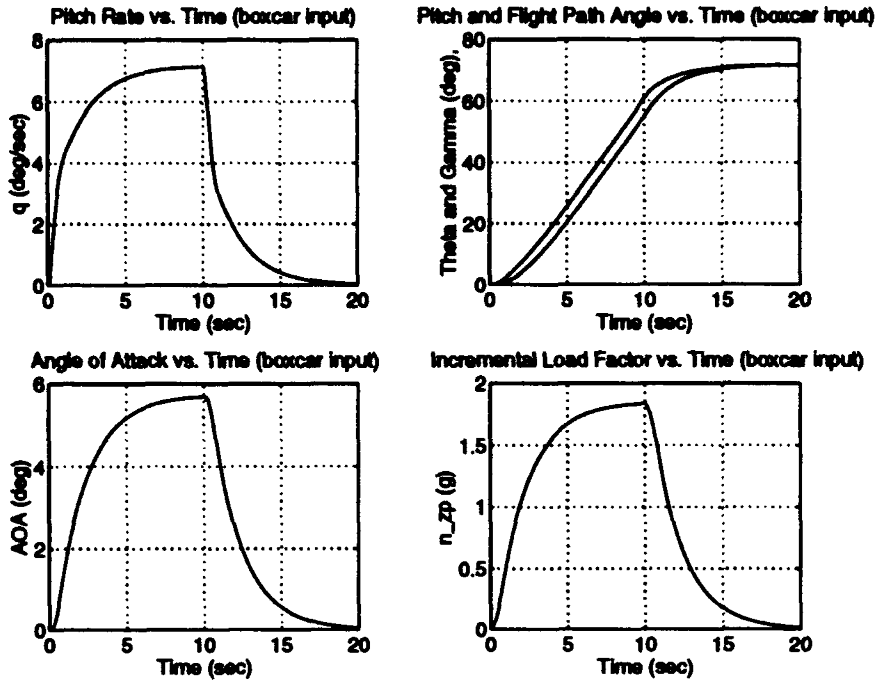

Figure D.49. Calspan Configuration 2J Time Responses

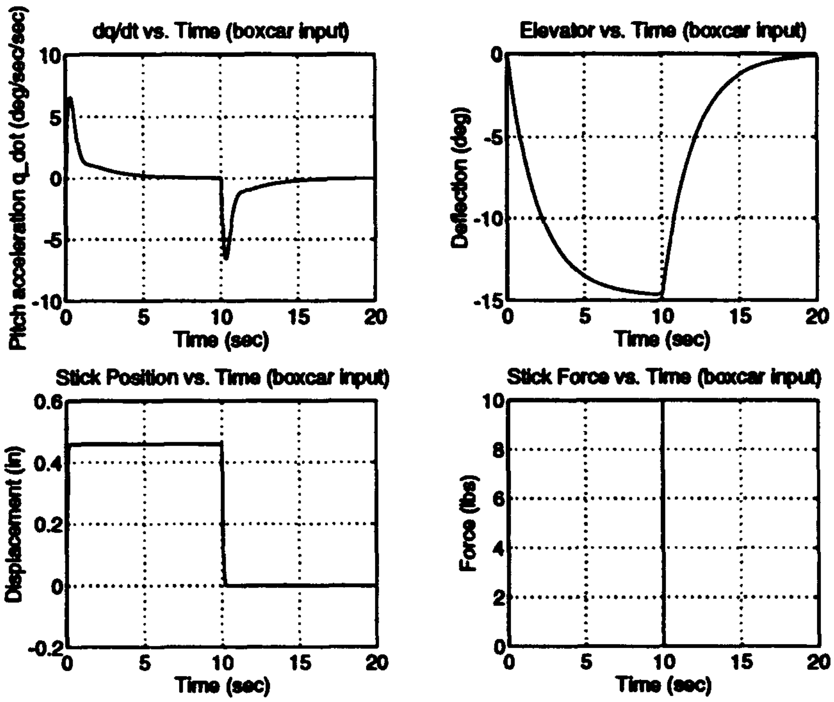

Figure D.50. Calspan Configuration 2J Time Responses

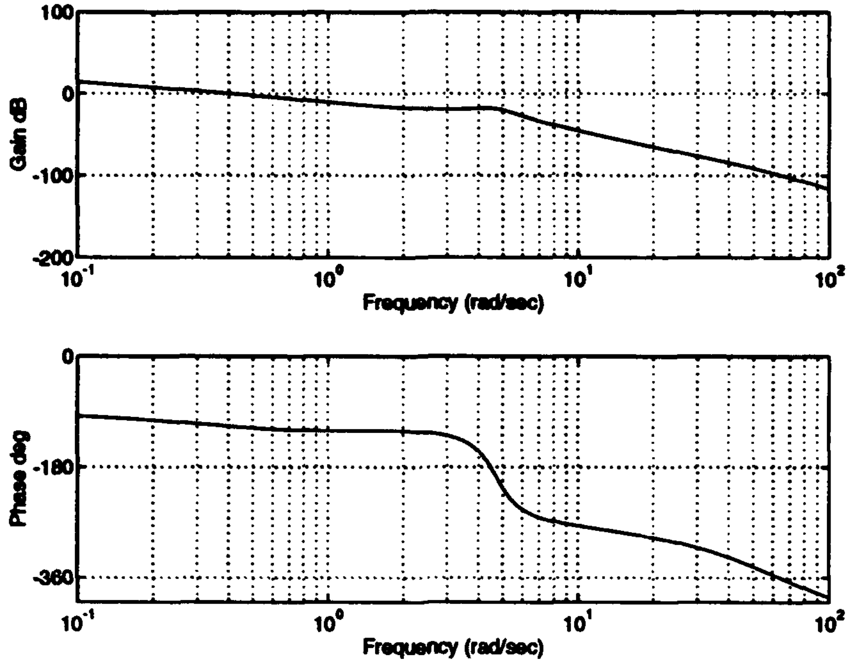

Figure D.51. Calspan Configuration 5E θ/F_{es} Frequency Response

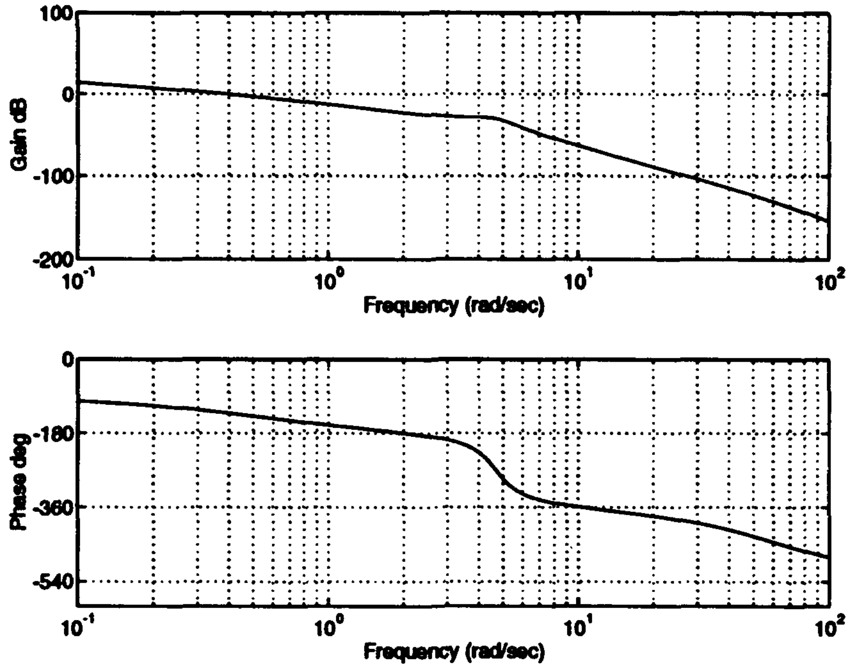

Figure D.52. Calspan Configuration 5E γ/F_{es} Frequency Response

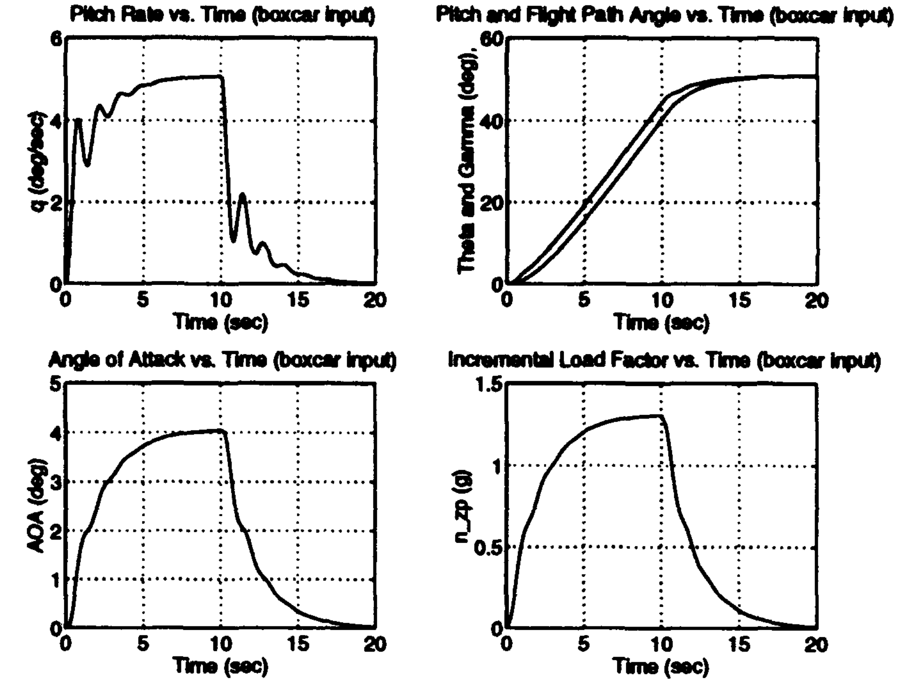

Figure D.53. Calspan Configuration 5E Time Responses

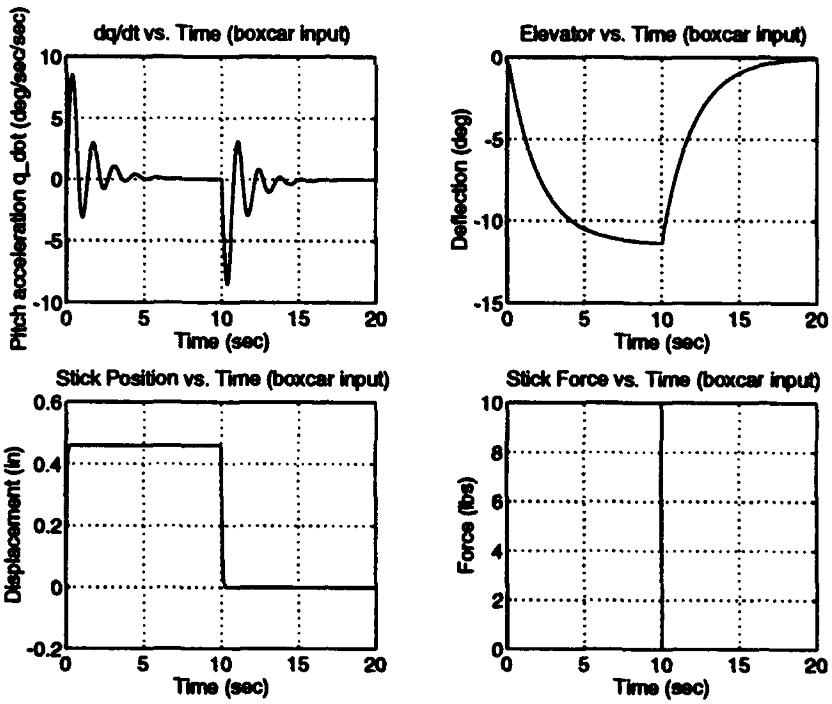

Figure D.54. Calspan Configuration 5E Time Responses

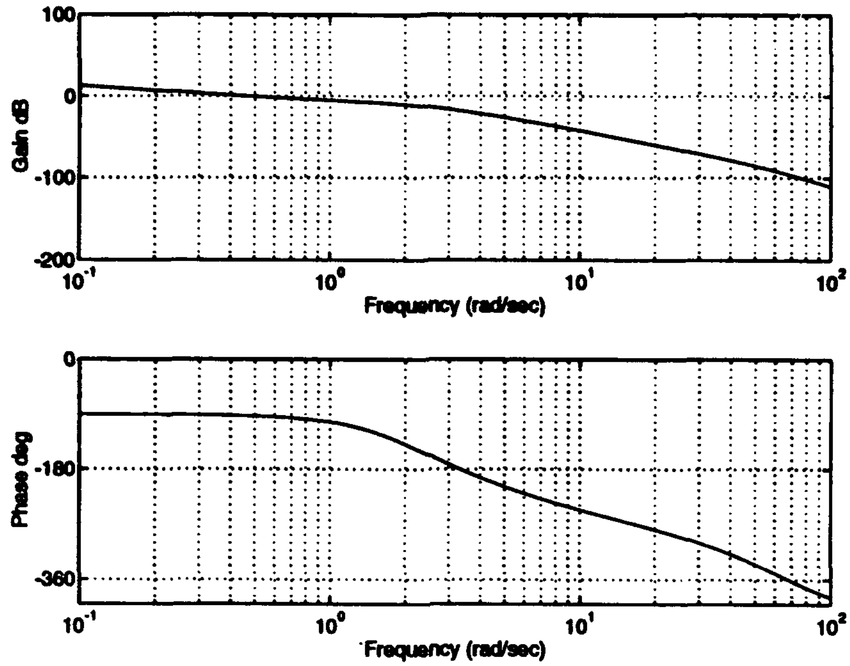

Figure D.55. Calspan Configuration 1E θ/F_{es} Frequency Response

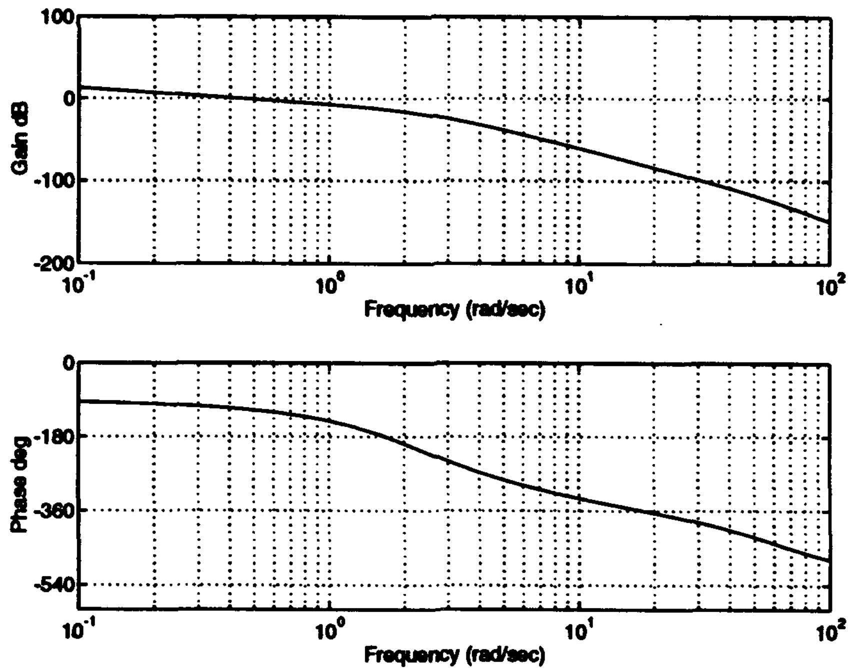

Figure D.56. Calspan Configuration 1E γ/F_{es} Frequency Response

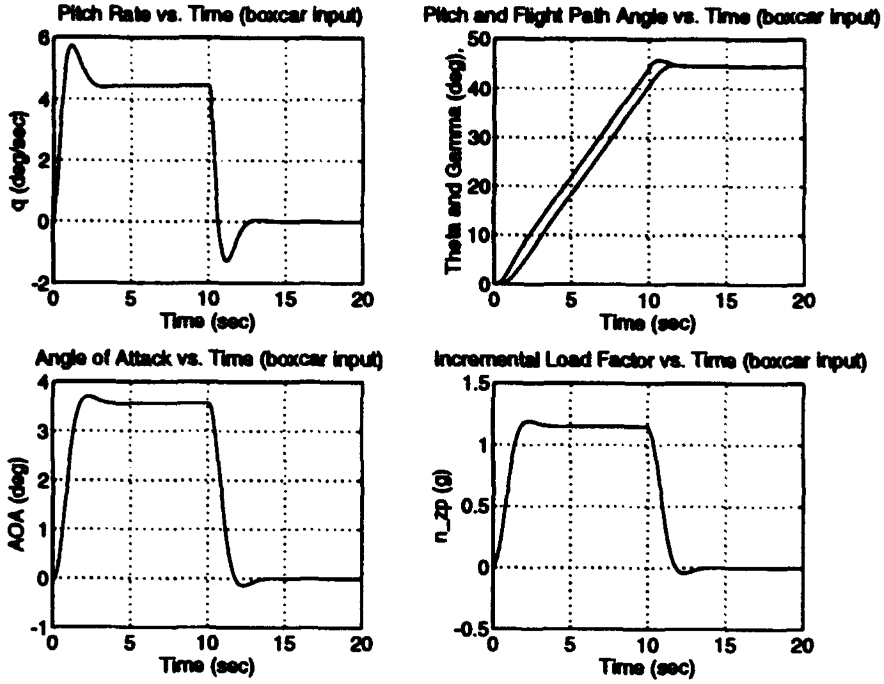

Figure D.57. Calspan Configuration 1E Time Responses

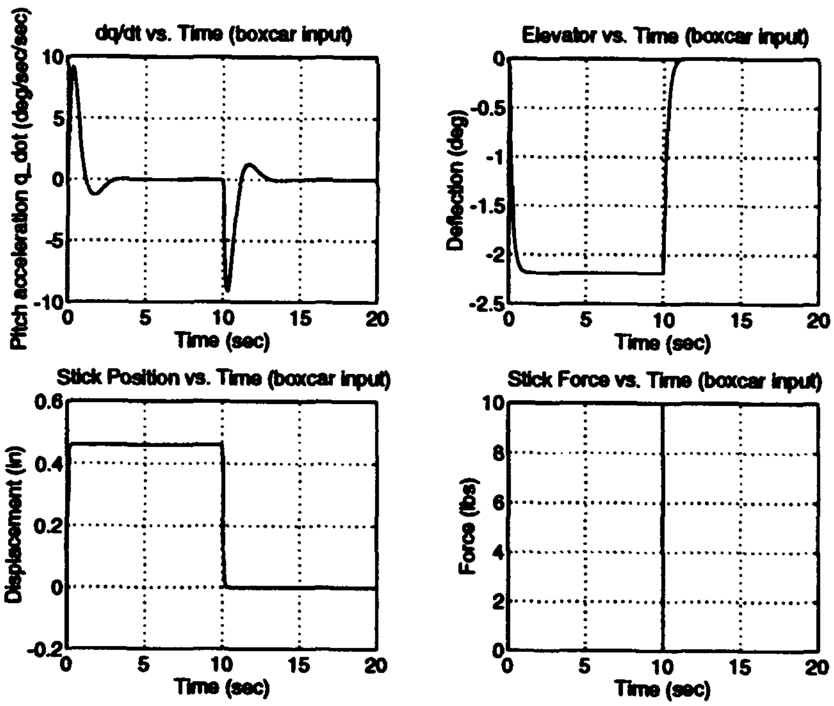

Figure D.58. Calspan Configuration 1E Time Responses

Appendix E. *HAVE GAS Configurations*

E.1 Introduction

The HAVE GAS configurations were modeled in SIMULINK using the equations of motion described here. Although it is possible to model a hybrid digital and analog FCS using SIMULINK, all configurations were modeled in the continuous time domain. The location and dynamics for the various filters were provided by Calspan. A first order Páde approximation was used to model the 23 msec to 28 msec (25 msec nominal) computational time delay. A second order actuator model was used.

E.2 RSS Fighter Simulation

The RSS fighter was simulated using the analog NT-33A VSS for all fourteen HAVE GAS configurations. Figure E.1 is a SIMULINK block diagram of the NT-33A VSS.

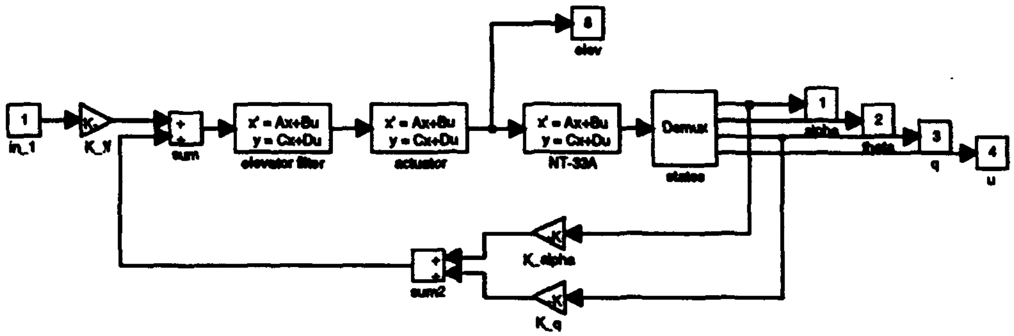

Figure E.1. SIMULINK Block Diagram of NT-33A VSS

The four aircraft states (in order) are α, θ, q, and u where angles and angular rates are in deg and deg/sec respectively and velocity is in fps. The following gains, transfer functions, and state-representations describe the dynamics for each of the blocks in Figure

E.1. The transfer functions were converted into state space representations for use in SIMULINK. State space realizations of transfer functions are given in Appendix C.

Feedforward gain

$$K_{ff} = 1.0 \tag{E.1}$$

NT-33A elevator filter

$$G(s) = \frac{140^2}{\left[s^2 + 2(0.7)(140)s + 140^2\right]} \tag{E.2}$$

NT-33A actuator

$$G(s) = \frac{63^2}{\left[s^2 + 2(0.75)(63)s + 63^2\right]} \tag{E.3}$$

NT-33A state-space model

$$A_{NT\text{-}33A} = \begin{bmatrix} -1.2300e+00 & -2.0000e-03 & 1 & -7.4485e+00 \\ 0 & 0 & 1 & 0 \\ -3.9300e+00 & -1.0000e-03 & -1.8300e+00 & +3.8961e+00 \\ 1.4486e-03 & -1.3450e-03 & -4.5379e-04 & -3.2000e-02 \end{bmatrix} \tag{E.4}$$

$$B_{NT\text{-}33A} = \begin{bmatrix} -5.3000e-02 \\ 0 \\ -7.7500e+00 \\ 1.7453e-05 \end{bmatrix} \tag{E.5}$$

$$C_{NT\text{-}33A} = I_{4\times4} \tag{E.6}$$

$$D_{NT\text{-}33A} = 0_{4\times1} \tag{E.7}$$

Feedback gains

$$K_\alpha = -0.57905 \quad \text{deg/deg}$$
$$K_q = -0.22405 \quad \text{deg/deg/sec} \tag{E.8}$$

The above gains were chosen to place the short period poles of the simulated RSS fighter at

$$\frac{1}{T_{sp1}} = -1.6817e+00 \quad \text{rad/sec}$$
$$\frac{1}{T_{sp2}} = +2.3506e-01 \quad \text{rad/sec} \tag{E.9}$$

The "phugoid" poles of the RSS fighter are now also first-order modes at

$$\lambda_{p_1} = -5.1677e-02 \quad \text{rad/sec}$$
$$\lambda_{p_2} = +3.1713e-02 \quad \text{rad/sec} \tag{E.10}$$

The NT-33A VSS dynamics were grouped into one block (labeled VSS) for use in subsequent block diagrams.

E.3 RCAH and ACAH Response-Type Simulation

The RCAH and ACAH response-types were simulated using the digital NT-33A flight control system. Figure E.2 is an analog SIMULINK block diagram approximation of the digital FCS used for the RCAH and ACAH response-types.

The following gains, transfer functions, and state-representations describe the dynamics for each of the blocks in Figure E.2. The transfer functions were converted into state space representations for use in SIMULINK. State space realizations of transfer functions are given in Appendix C.

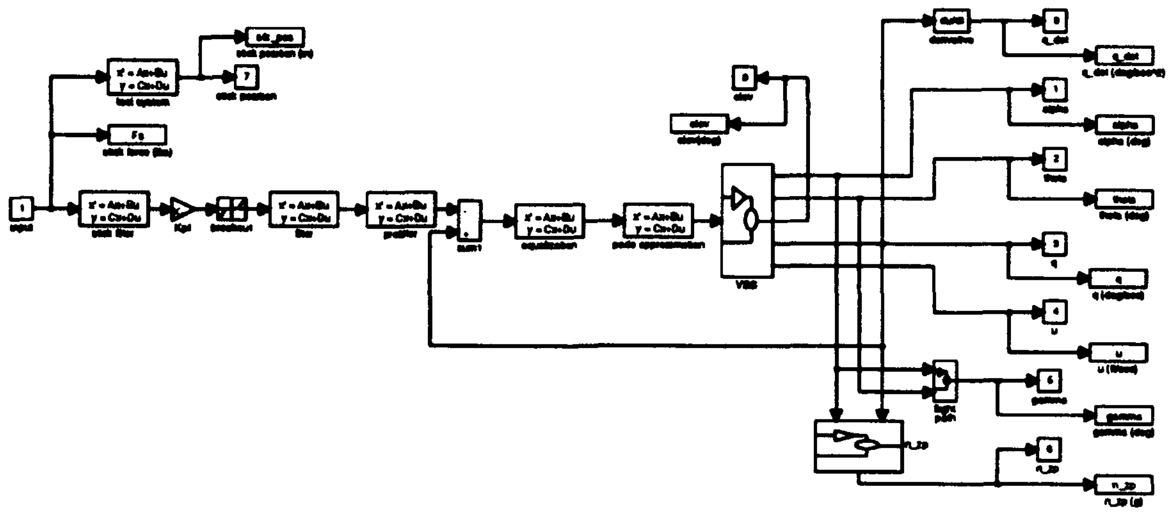

Figure E.2. SIMULINK Block Diagram of RCAH and ACAH Configurations[1]

Longitudinal Feel System (8.5 lb/in longitudinal static stick force)

$$\frac{\delta_{es}}{F_{es}} = \frac{\frac{26^2}{8.5}}{\left[s^2 + 2(0.7)(26)s + 26^2\right]} \tag{E.11}$$

Stick Filter

$$G(s) = \frac{100}{(s+100)} \tag{E.12}$$

Command Gains

$$G(s) = K_{pf} \tag{E.13}$$

Where K_{pf} for each configuration is given in Table E.1.

Breakout

$$\pm 0.75 \quad \text{lb} \tag{E.14}$$

---

[1]For frequency response plots, the breakout was removed and the derivative blocks were approximated using Eqn D.16.

Table E.1. HAVE GAS RCAH and ACAH Command Gains[2]

HAVE GAS RCAH and ACAH Command Gains					
Configuration			K_{pf}	K_{pf}	K_{pf}
R1	R1X	A1	1.88	1.67	2.86
R2	R2X	A2	1.14	1.27	1.90
R3	R3X	A3	0.93	1.16	1.20
R4	R4X	A4	0.70	0.97	0.72

Filter

$$G(s) = \frac{40}{s+40} \tag{E.15}$$

Prefilter

RCAH

$$G(s) = 1 \tag{E.16}$$

RCAH Extended Bandwidth

$$G(s) = \frac{(s+1.5)}{\left(s+\frac{1}{T_q}\right)} \tag{E.17}$$

ACAH

$$G(s) = \frac{s}{\left(s+\frac{1}{T_q}\right)} \tag{E.18}$$

Values for $1/T_q$ are listed in Table E.2.

Equalization

[2]Command gains were determined by matching SIMULINK time histories with aircraft time histories to a step input.

$$G(s) = K_q + \frac{K_q}{T_q}\frac{1}{s} = \frac{K_q\left(s+\frac{1}{T_q}\right)}{s} = \frac{K_q}{T_q}\frac{\left(T_q s+1\right)}{s} \tag{E.19}$$

Table E.2. HAVE GAS Equalization Parameters

HAVE GAS Equalization Parameters				
Configuration	K_q (deg/deg/sec)	$1/T_q$ (1/sec)	K_q/T_q (—)	$[\zeta', \omega']$ (–, rad/sec)
R1, R1X, A1	4.5300e−01	2.0	9.0600e−01	[0.7, 2.60]
R2, R2X, A2	5.9000e−01	2.5	1.4750e+00	[0.7, 3.65]
R3, R3X, A3	7.3600e−01	3.0	2.2080e+00	[0.7, 4.82]
R4, R4X, A4	8.8700e−01	3.5	3.1045e+00	[0.7, 6.21]

First order Padé approximation (simulate 25 msec computational time delay)

$$G(s) = -\frac{(s-80)}{(s+80)} \tag{E.20}$$

Dynamics for flight path, normal acceleration at the pilot station, and derivative approximations are all equivalent to those discussed in Appendix D (Eqns D.12, D.14, D.16).

E.4 Conventional Response-Type Simulation

The conventional response-types were also simulated using the digital NT-33A flight control system. Figure E.3 is an analog SIMULINK block diagram approximation of the digital FCS used for the conventional response-types.

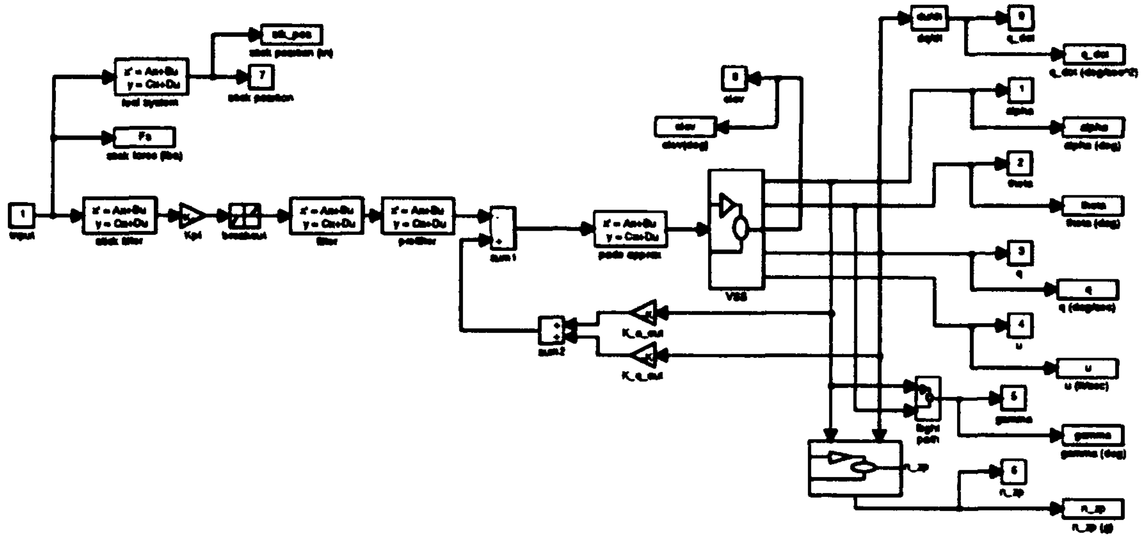

Figure E.3. SIMULINK Block Diagram of Conventional Configurations[3]

The gains, transfer functions, and state-representations described in the previous sections for similarly labeled blocks apply with the following exceptions. The transfer functions were converted into state space representations for use in SIMULINK. State space realizations of transfer functions are given in Appendix C.

Longitudinal Feel System (22.0 lb/in longitudinal static stick force)

$$\frac{\delta_{es}}{F_{es}} = \frac{\frac{31^2}{22}}{\left[s^2 + 2(1.0)(31)s + 31^2\right]} \tag{E.21}$$

Command Gains

$$\begin{aligned} K_{pf} &= 1.0 \quad \text{for configuration C1} \\ K_{pf} &= 2.4 \quad \text{for configuration C1X} \end{aligned} \tag{E.22}$$

Prefilter

Conventional (configuration C1)

---

[3]For frequency response plots, the breakout was removed and the derivative blocks were approximated using Eqn D.16.

$$G(s) = 1 \tag{E.23}$$

Conventional Extended Bandwidth (configuration C1X)

$$G(s) = \frac{(s+2)}{(s+5)} \tag{E.24}$$

Feedback gains

$$\begin{aligned} K_{\alpha_{out}} &= 1.3560\text{e}+00 \quad \text{deg/deg} \\ K_{q_{out}} &= 5.8040\text{e}-01 \quad \text{deg/deg/sec} \end{aligned} \tag{E.25}$$

These gains result in short period dynamics of $[0.72, 4.5]$ for both configurations C1 and C1X.

E.5 Frequency Responses and Time Histories for HAVE GAS Configurations

The following figures are the θ/F_{es} and γ/F_{es} frequency responses and the time histories to a 10 lb boxcar input for the HAVE GAS configurations.

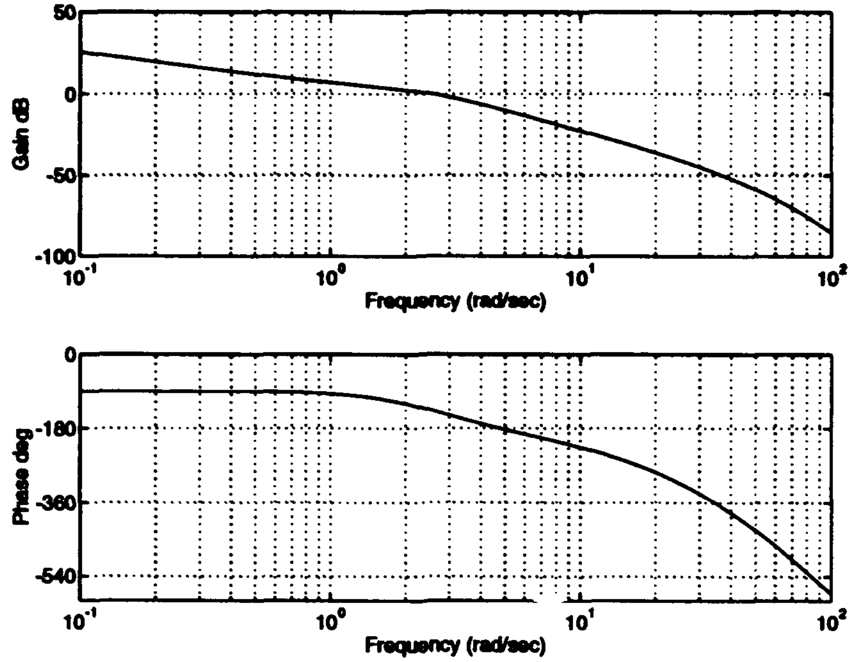

Figure E.4. HAVE GAS Configuration R1 θ/F_{es} Frequency Response

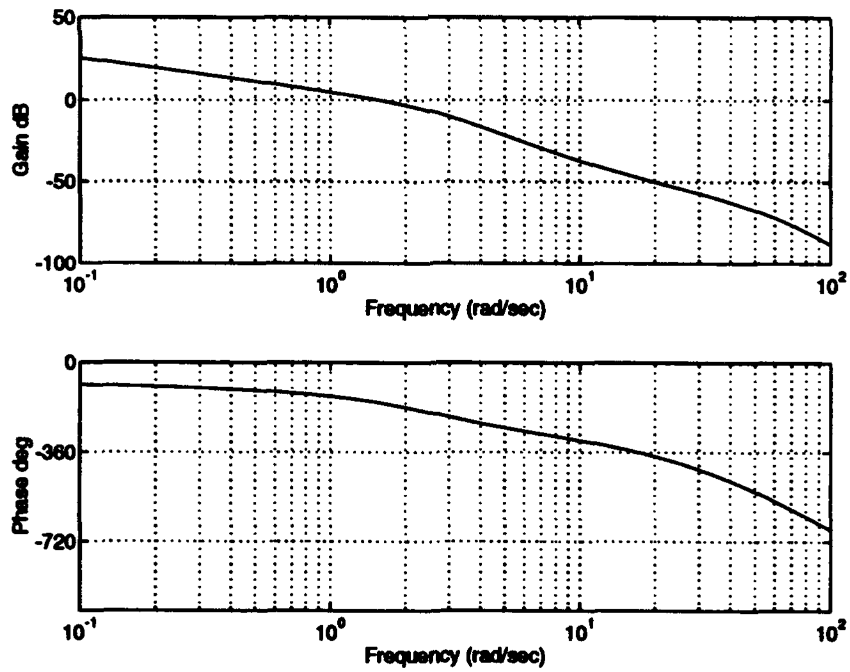

Figure E.5. HAVE GAS Configuration R1 γ/F_{es} Frequency Response

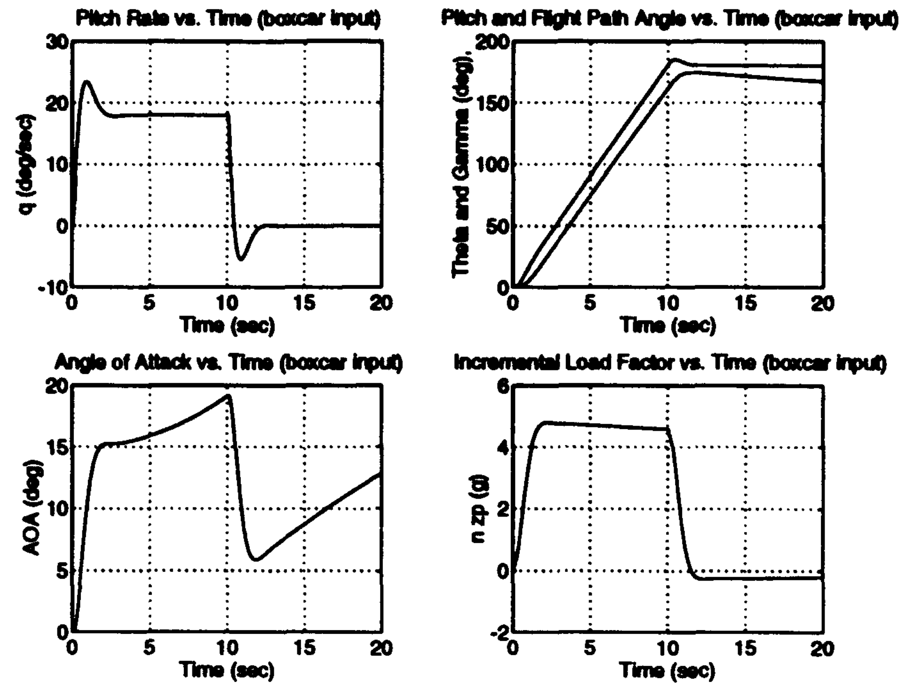

Figure E.6. HAVE GAS Configuration R1 Time Responses

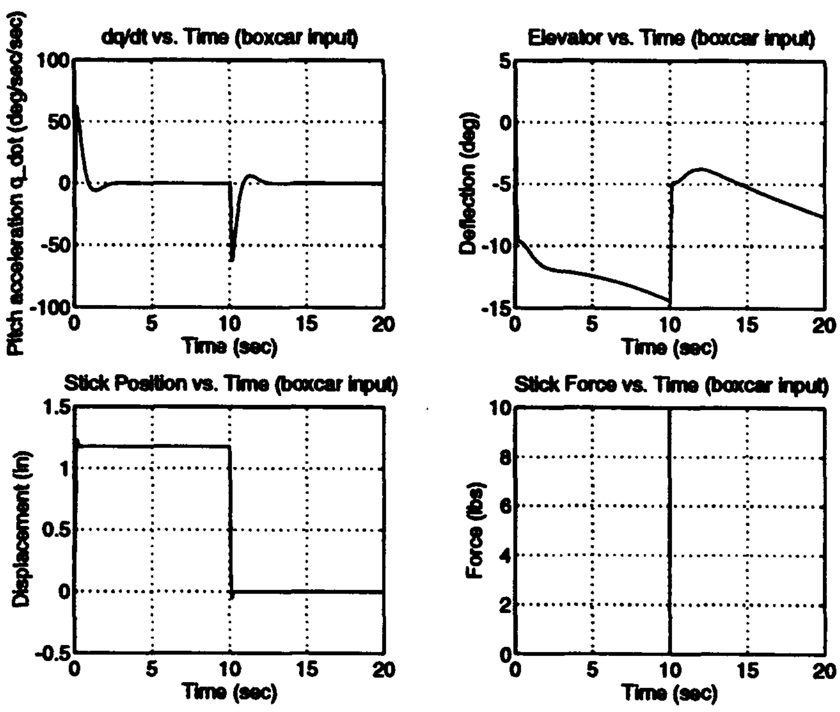

Figure E.7. HAVE GAS Configuration R1 Time Responses

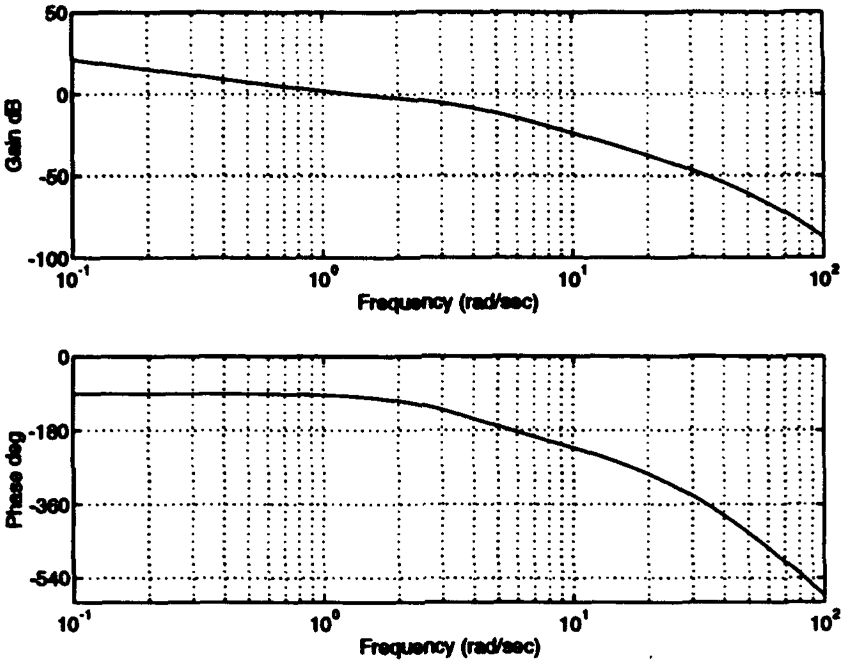

Figure E.8. HAVE GAS Configuration R2 θ/F_{es} Frequency Response

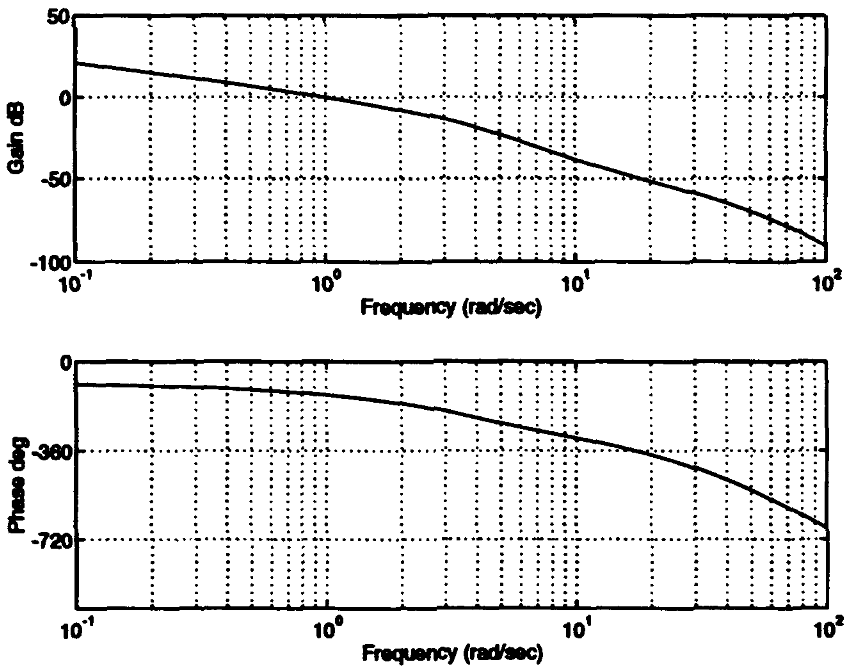

Figure E.9. HAVE GAS Configuration R2 γ/F_{es} Frequency Response

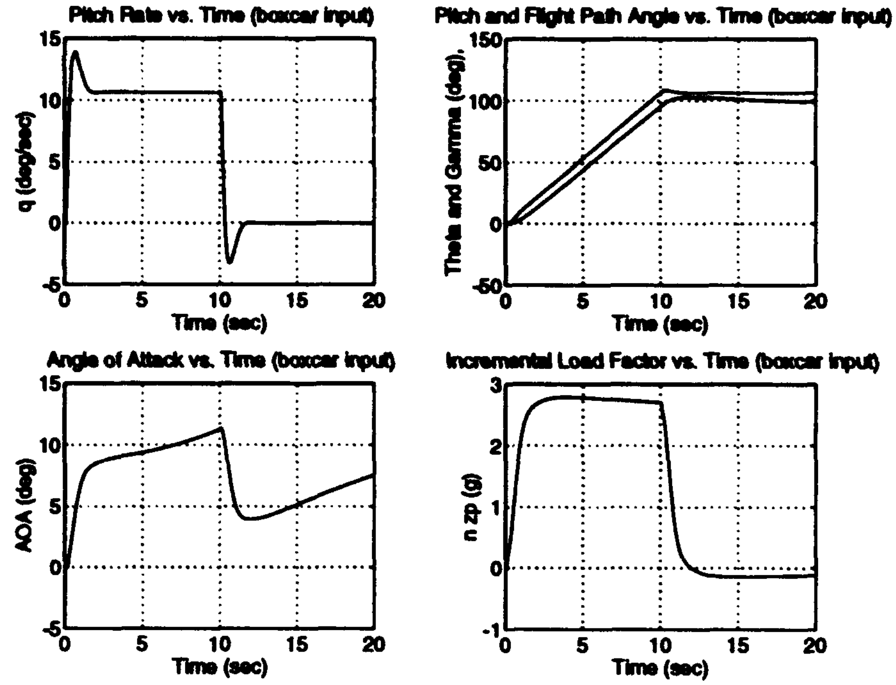

Figure E.10. HAVE GAS Configuration R2 Time Responses

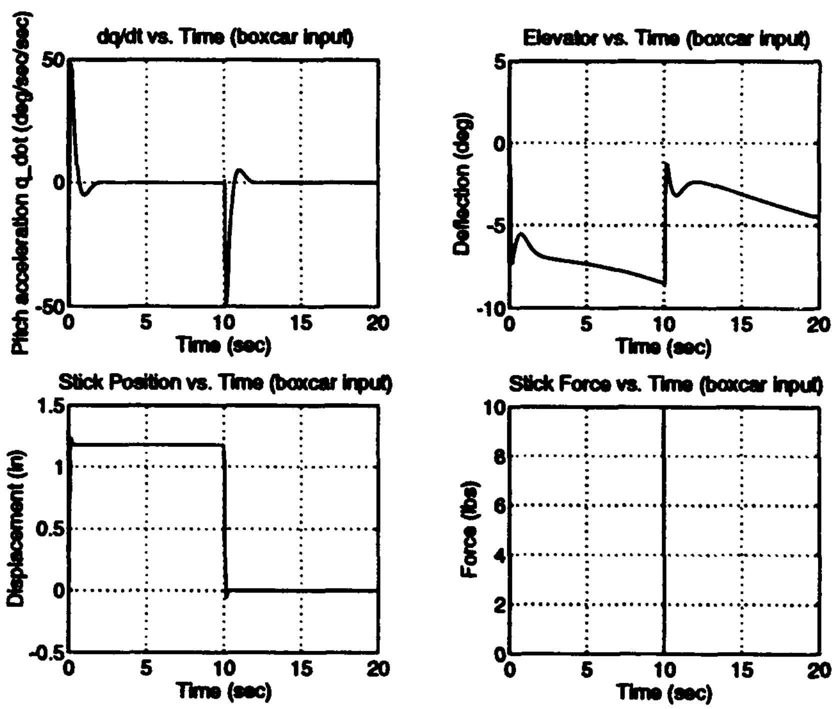

Figure E.11. HAVE GAS Configuration R2 Time Responses

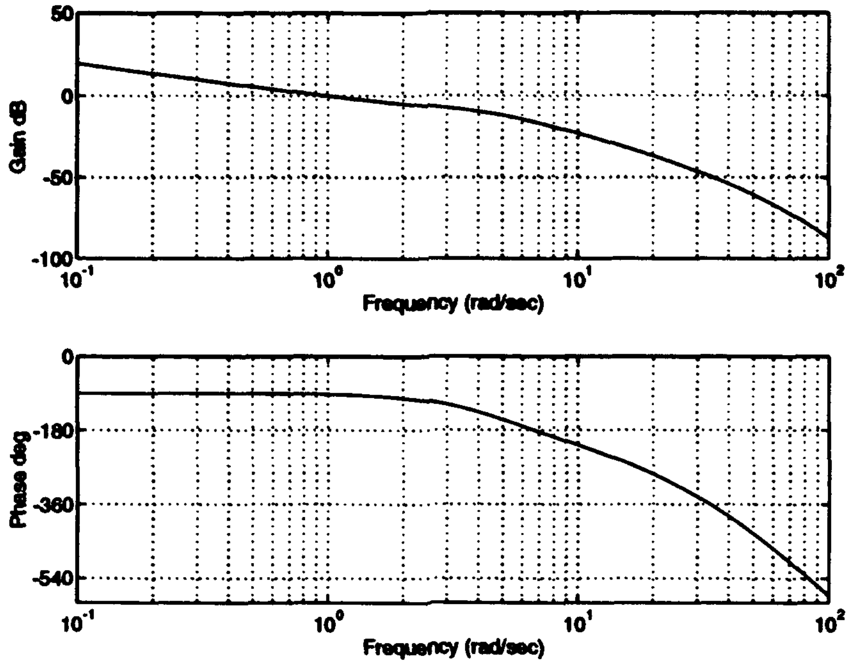

Figure E.12. HAVE GAS Configuration R3 θ/F_{es} Frequency Response

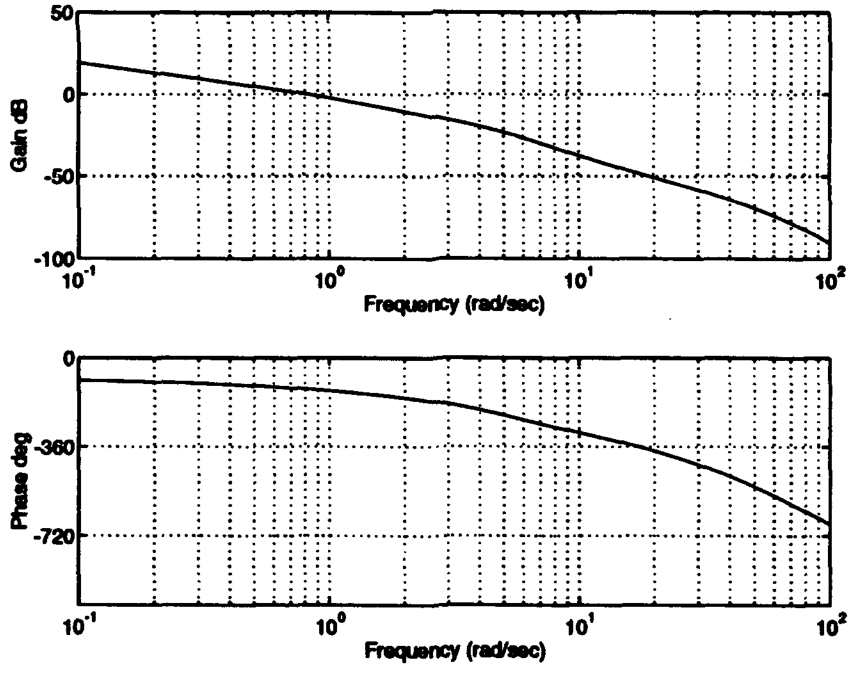

Figure E.13. HAVE GAS Configuration R3 γ/F_{es} Frequency Response

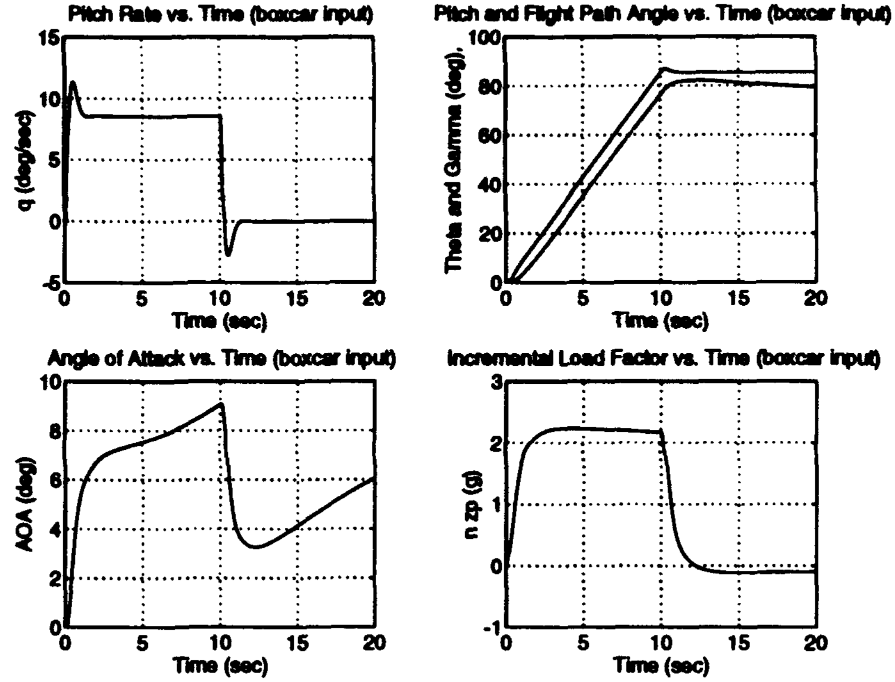

Figure E.14. HAVE GAS Configuration R3 Time Responses

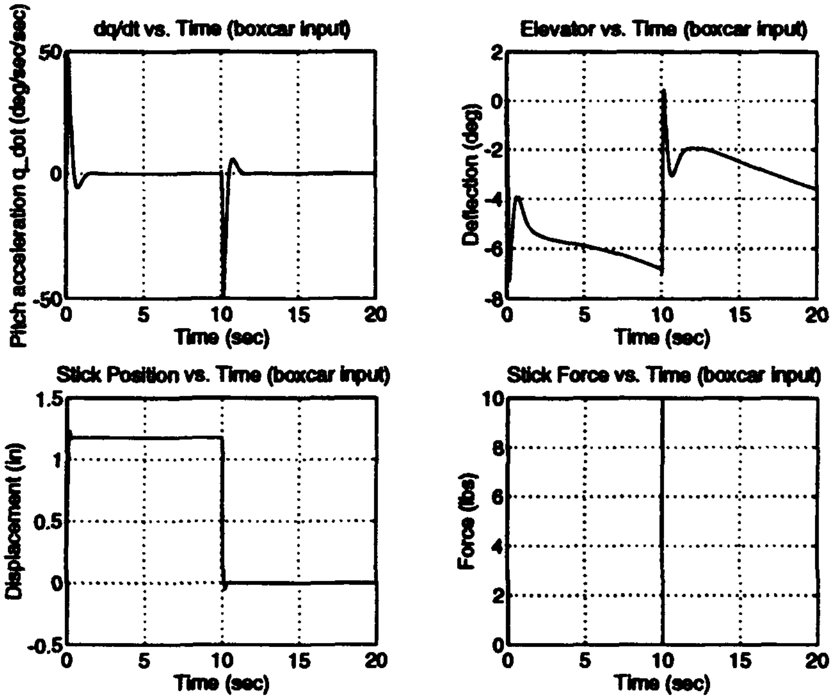

Figure E.15. HAVE GAS Configuration R3 Time Responses

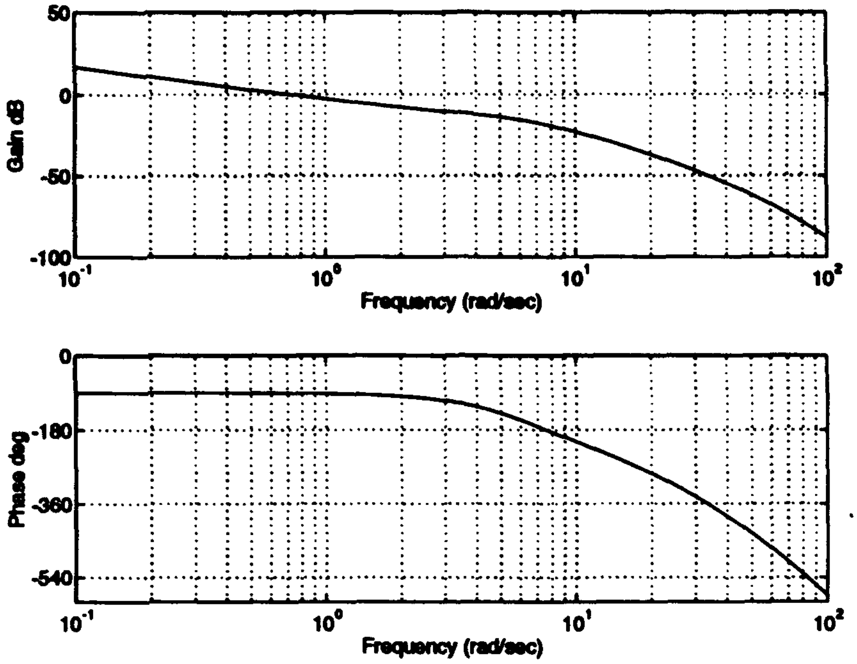

Figure E.16. HAVE GAS Configuration R4 θ/F_{es} Frequency Response

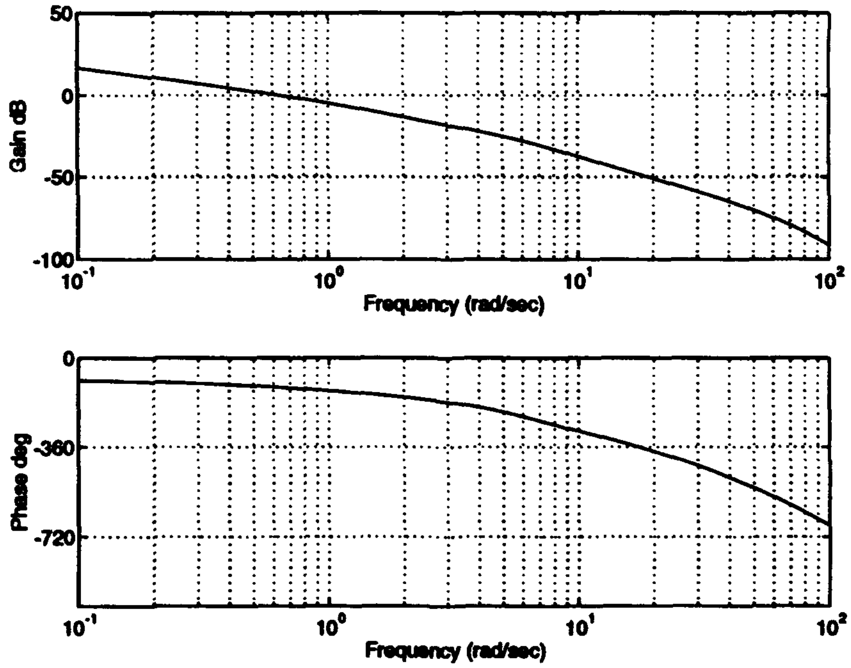

Figure E.17. HAVE GAS Configuration R4 γ/F_{es} Frequency Response

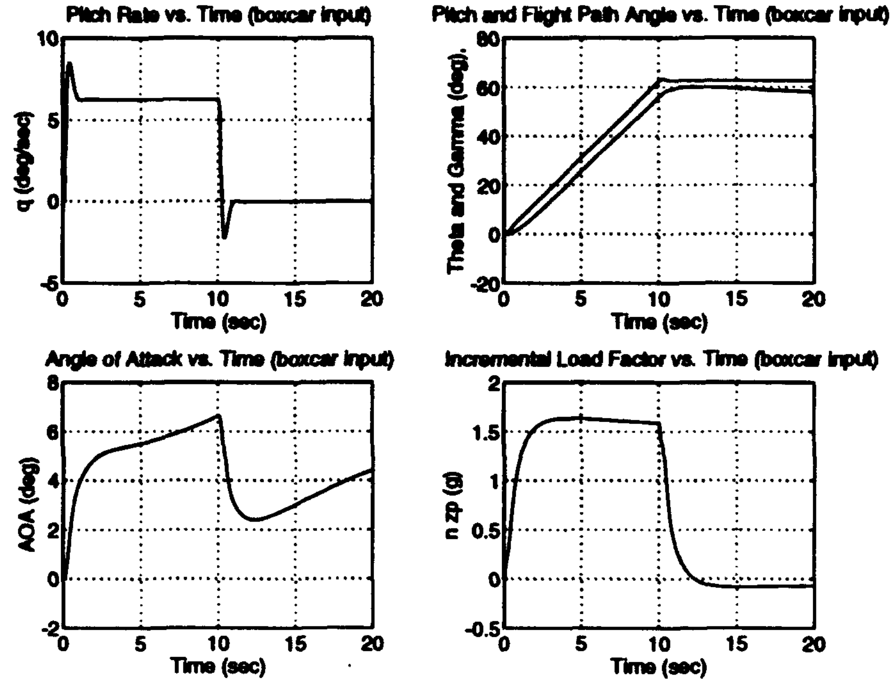

Figure E.18. HAVE GAS Configuration R4 Time Responses

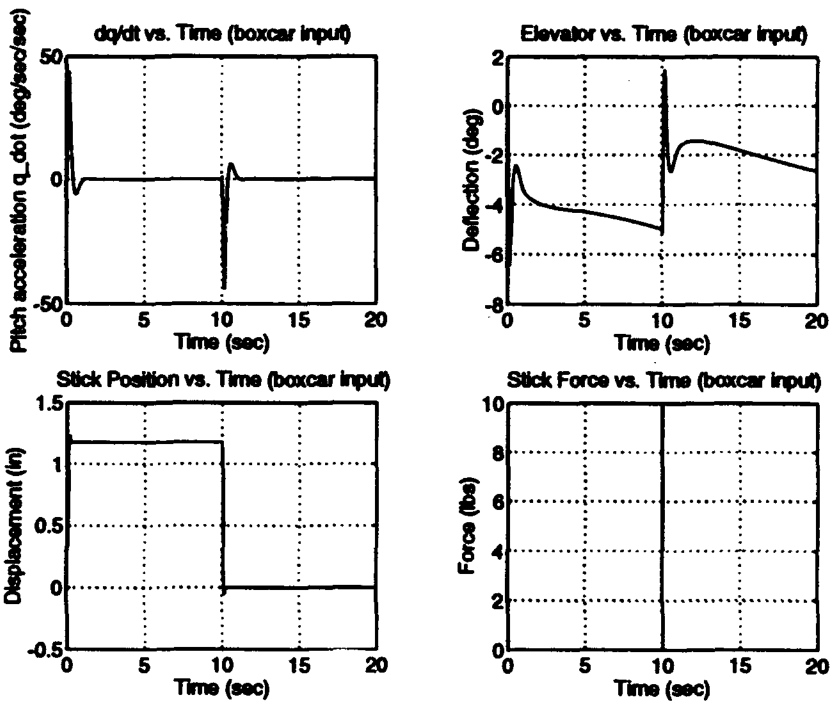

Figure E.19. HAVE GAS Configuration R4 Time Responses

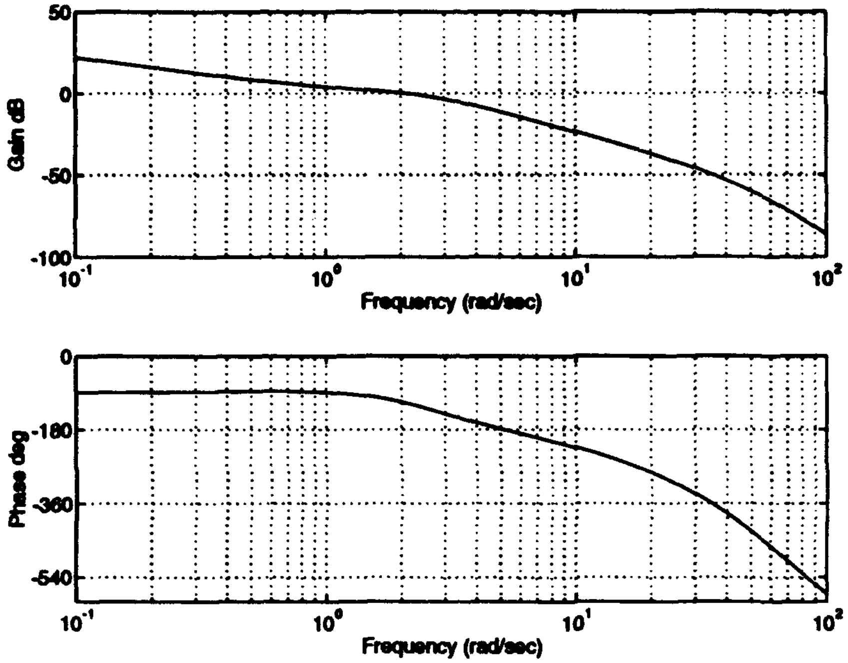

Figure E.20. HAVE GAS Configuration R1X θ/F_{es} Frequency Response

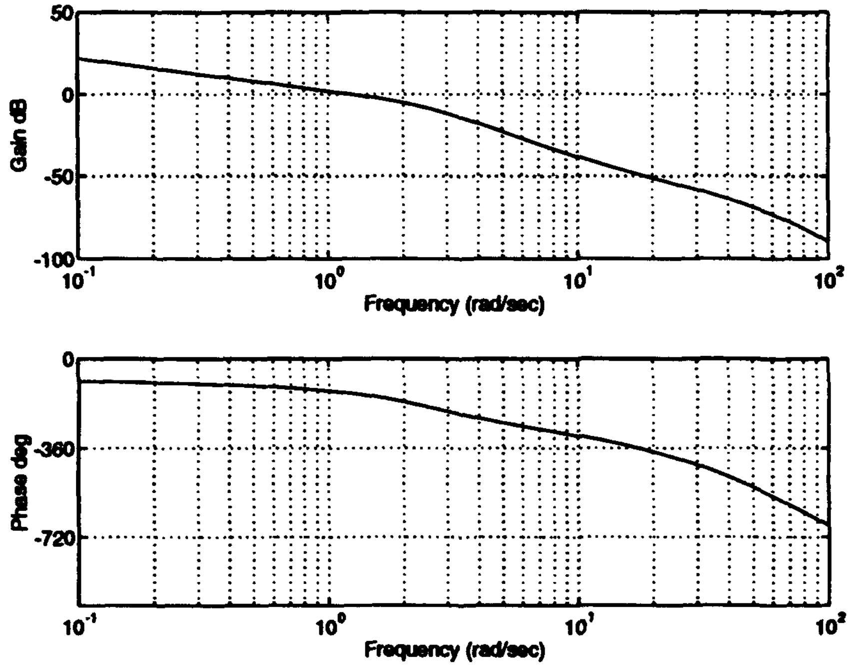

Figure E.21. HAVE GAS Configuration R1X γ/F_{es} Frequency Response

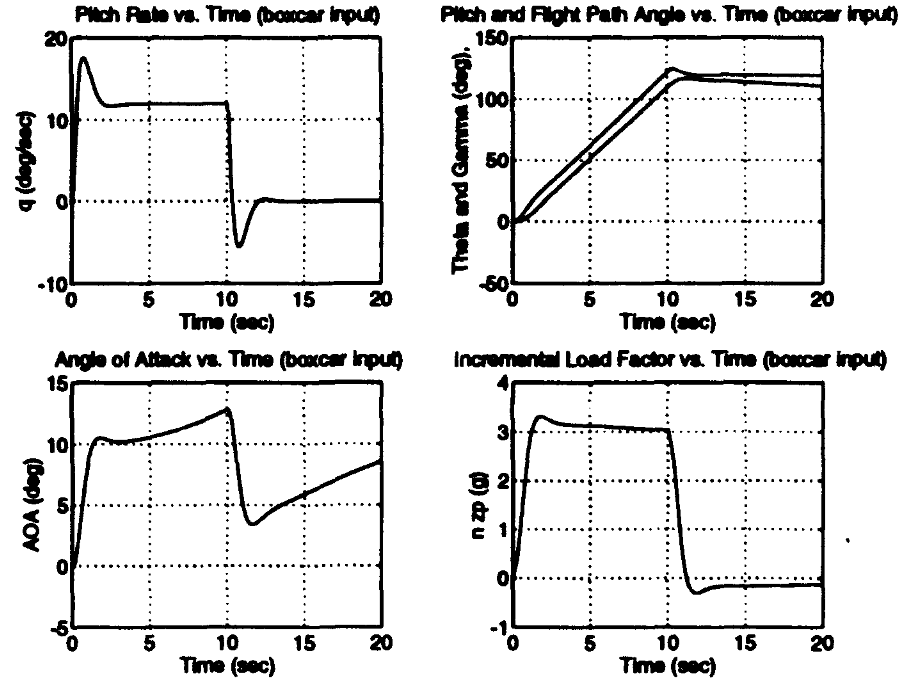

Figure E.22. HAVE GAS Configuration R1X Time Responses

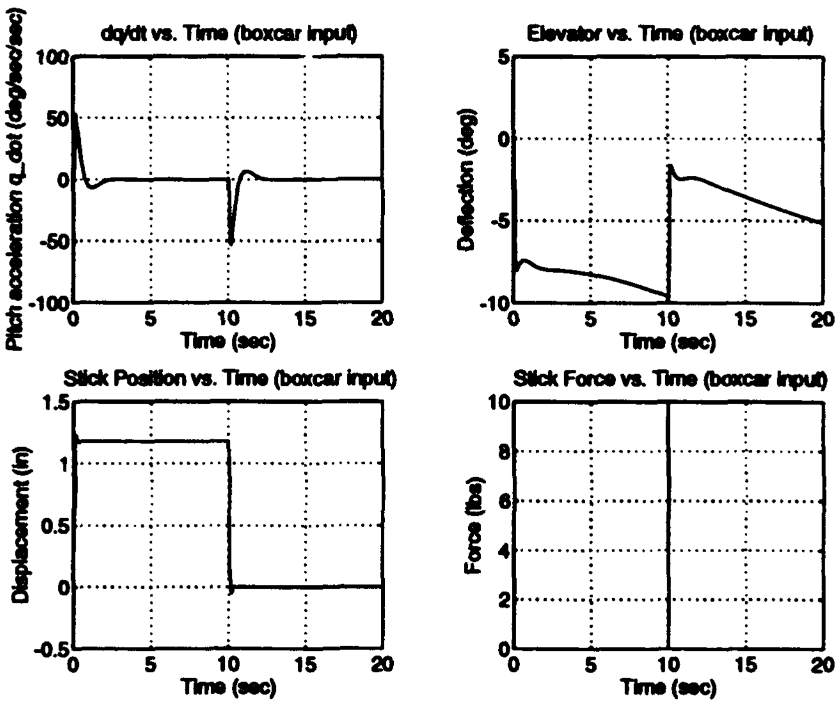

Figure E.23. HAVE GAS Configuration R1X Time Responses

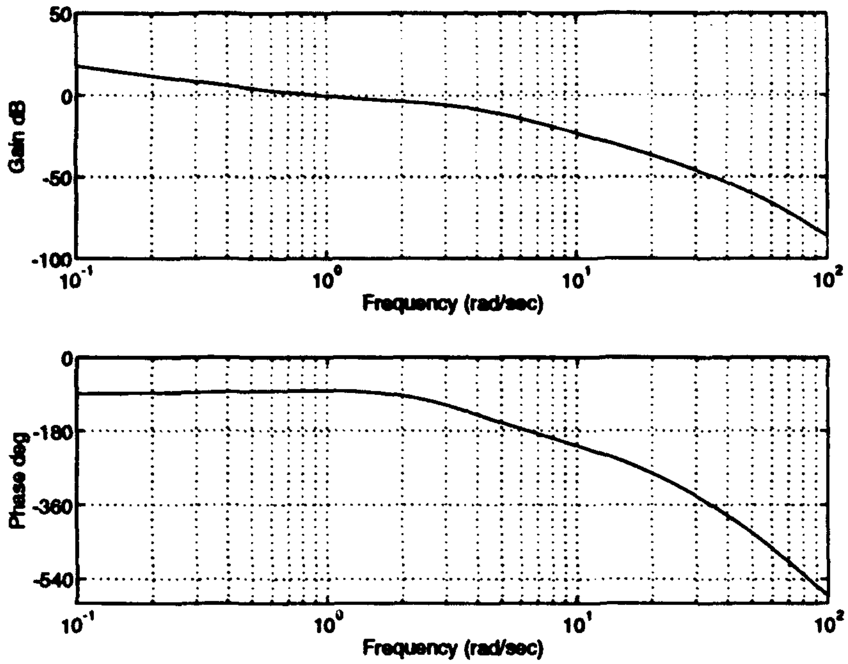

Figure E.24. HAVE GAS Configuration R2X θ/F_{es} Frequency Response

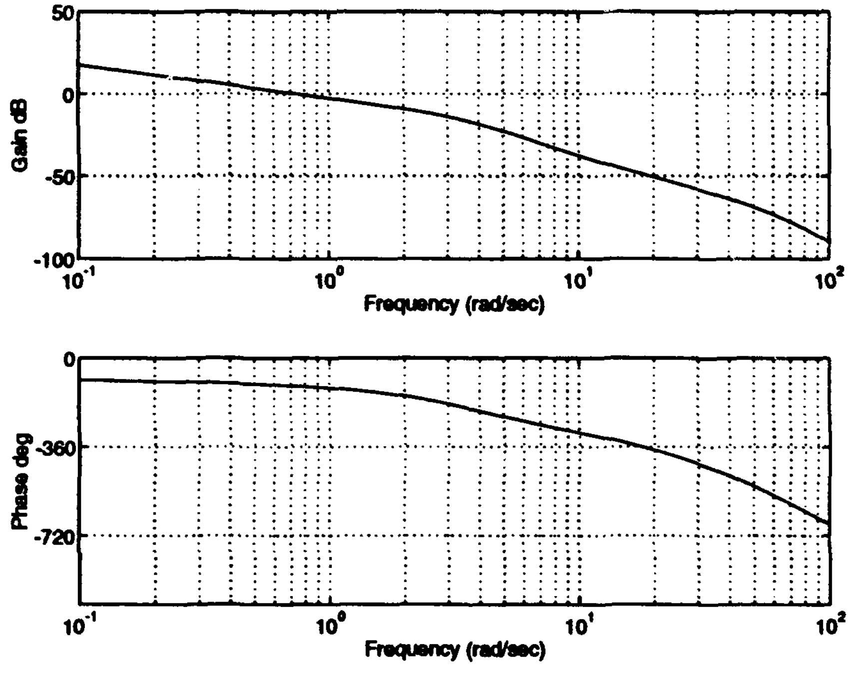

Figure E.25. HAVE GAS Configuration R2X γ/F_{es} Frequency Response

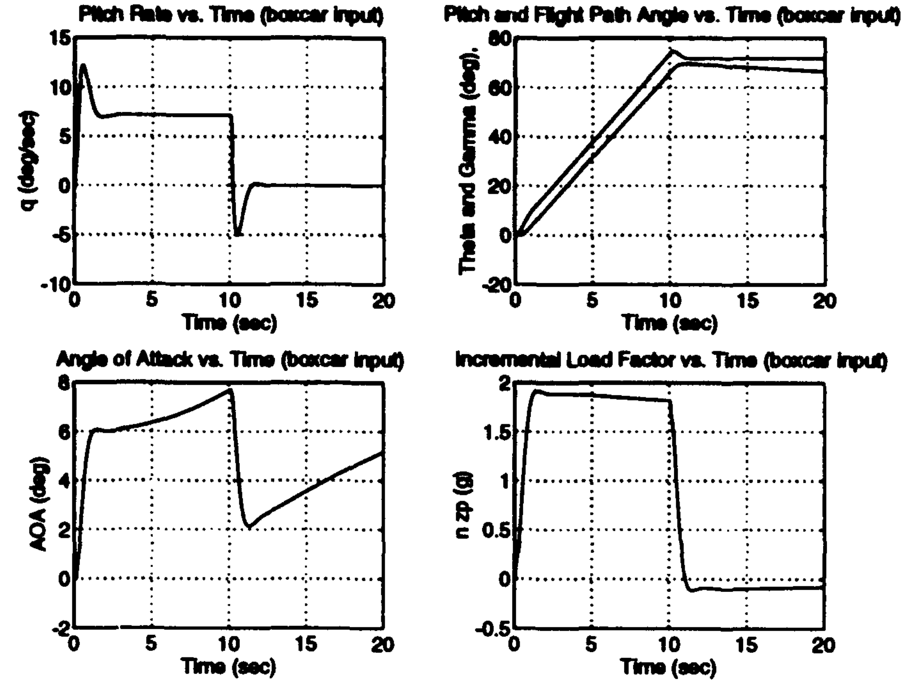

Figure E.26. HAVE GAS Configuration R2X Time Responses

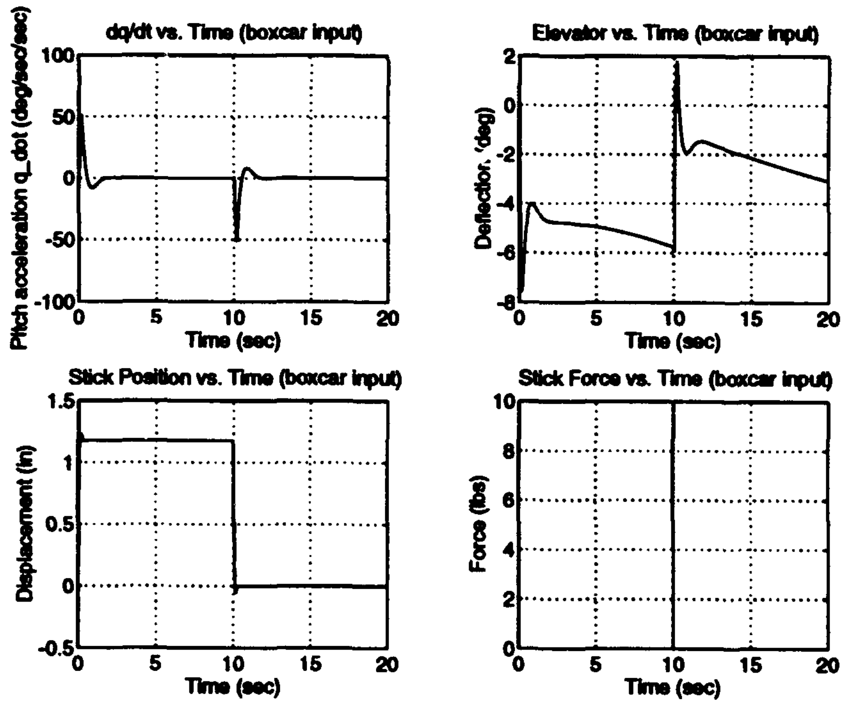

Figure E.27. HAVE GAS Configuration R2X Time Responses

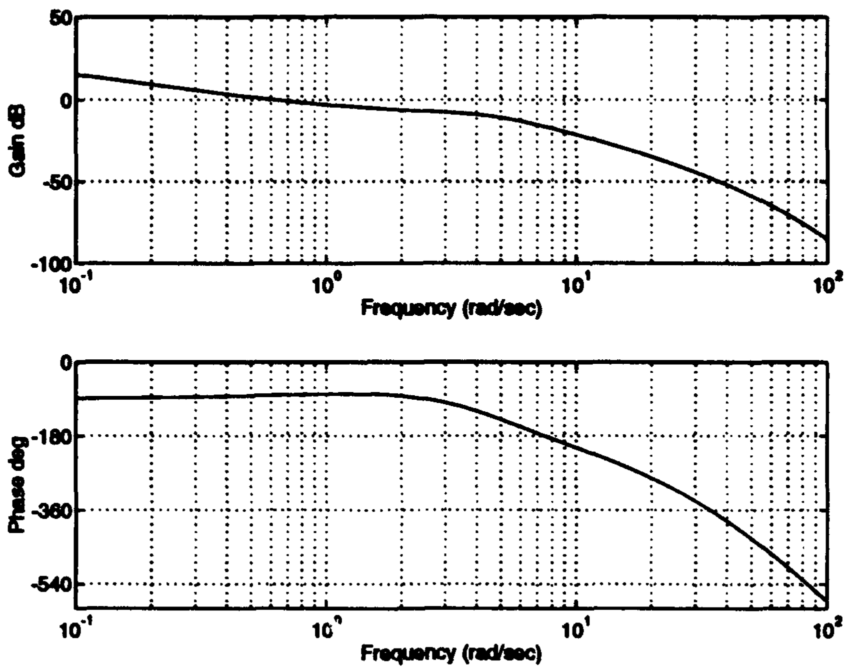

Figure E.28. HAVE GAS Configuration R3X θ/F_{es} Frequency Response

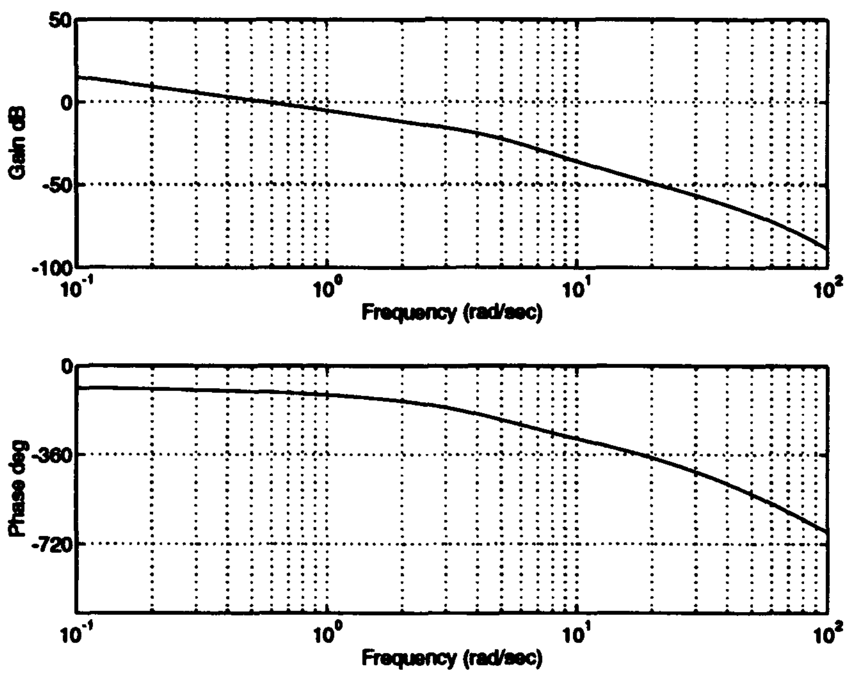

Figure E.29. HAVE GAS Configuration R3X γ/F_{es} Frequency Response

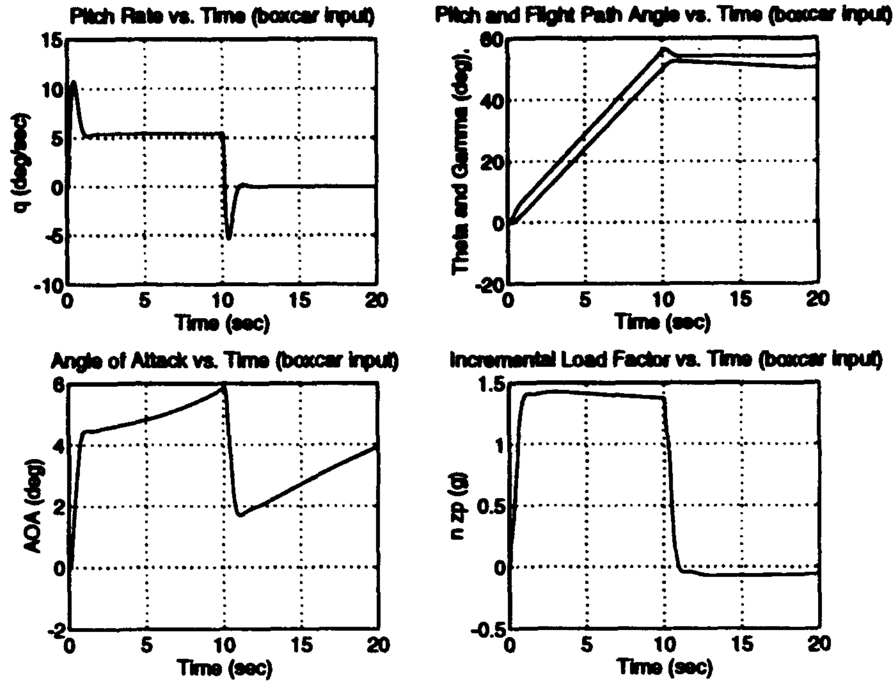

Figure E.30. HAVE GAS Configuration R3X Time Responses

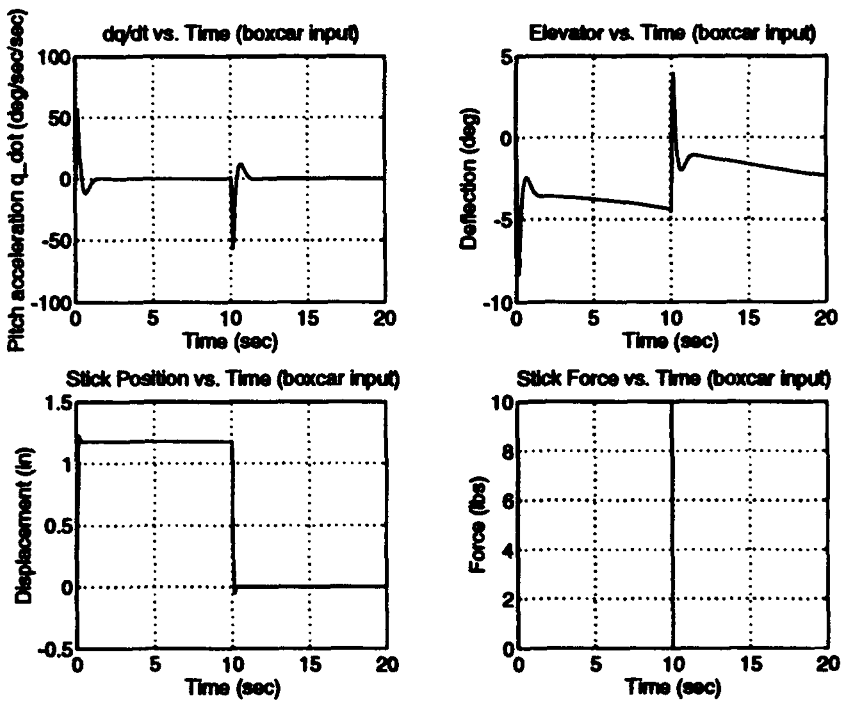

Figure E.31. HAVE GAS Configuration R3X Time Responses

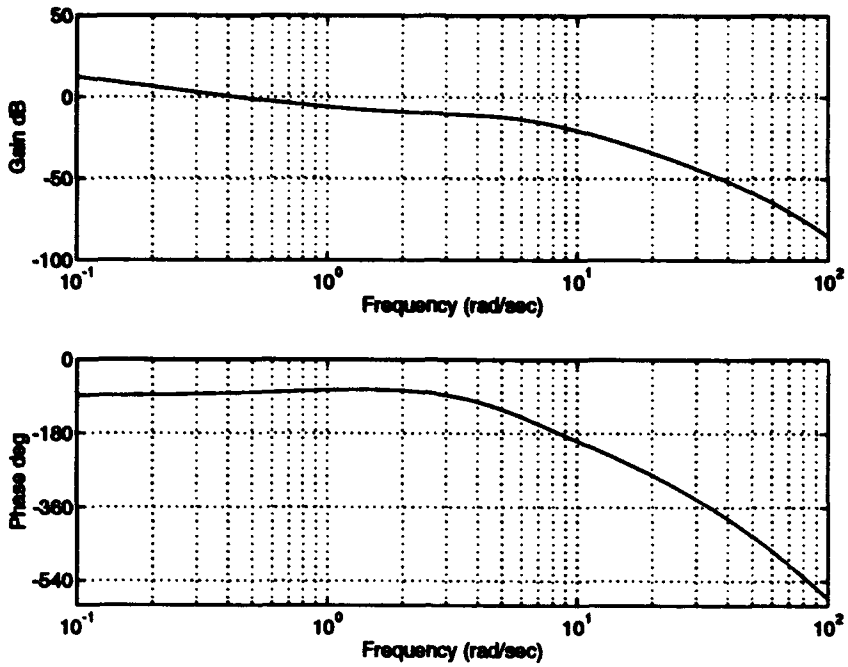

Figure E.32. HAVE GAS Configuration R4X θ/F_{es} Frequency Response

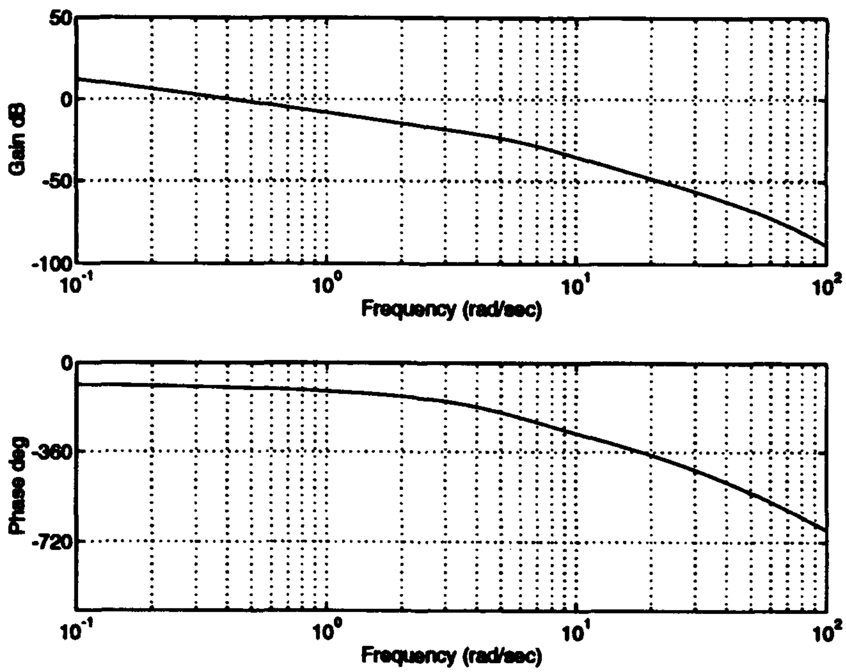

Figure E.33. HAVE GAS Configuration R4X γ/F_{es} Frequency Response

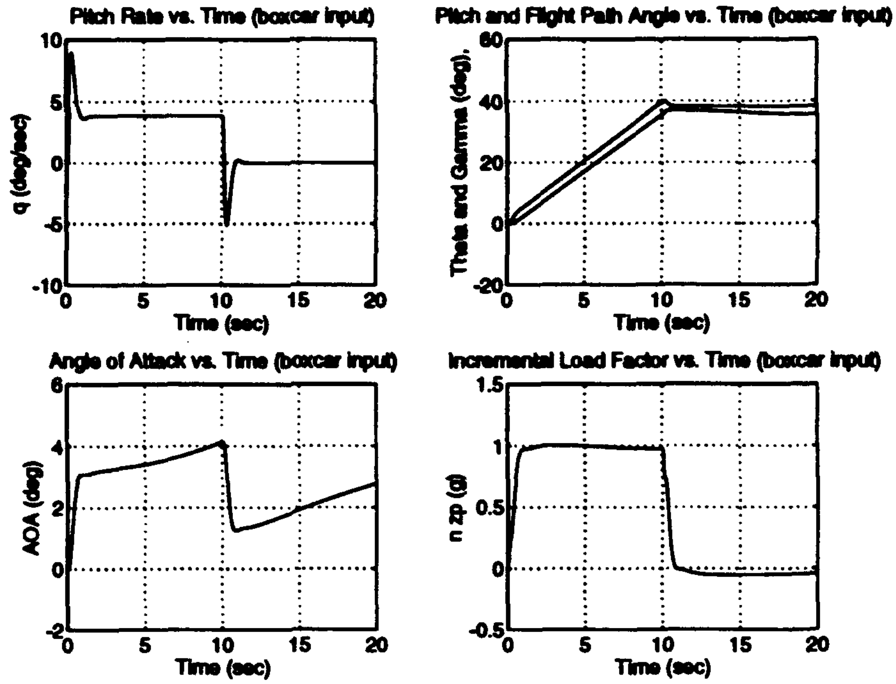

Figure E.34. HAVE GAS Configuration R4X Time Responses

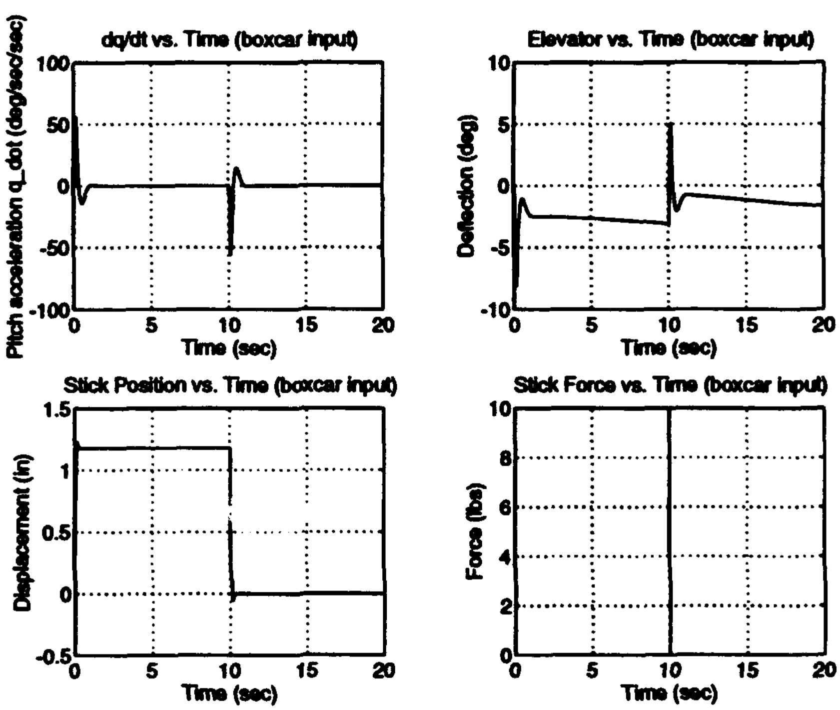

Figure E.35. HAVE GAS Configuration R4X Time Responses

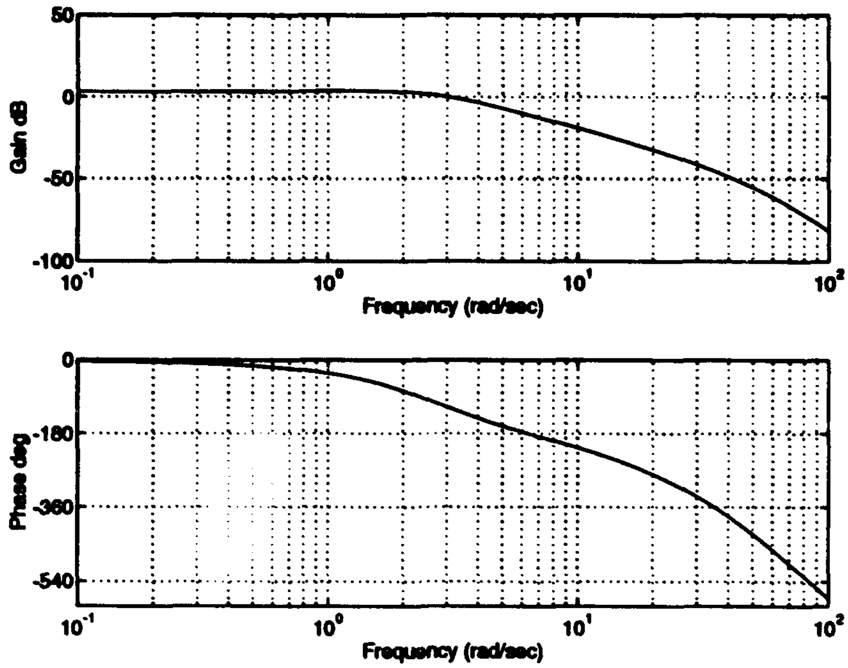

Figure E.36. HAVE GAS Configuration A1 θ/F_{es} Frequency Response

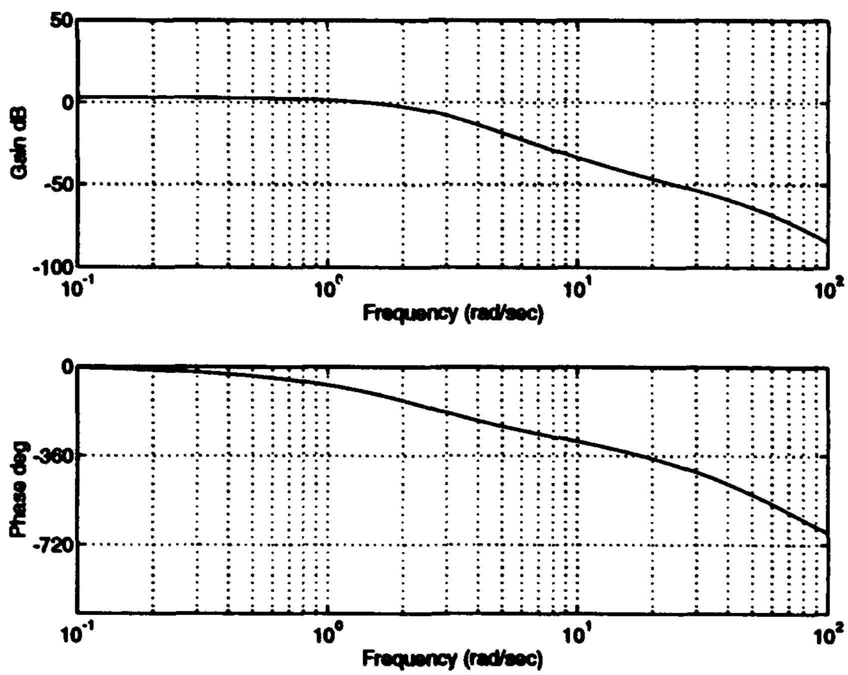

Figure E.37. HAVE GAS Configuration A1 γ/F_{es} Frequency Response

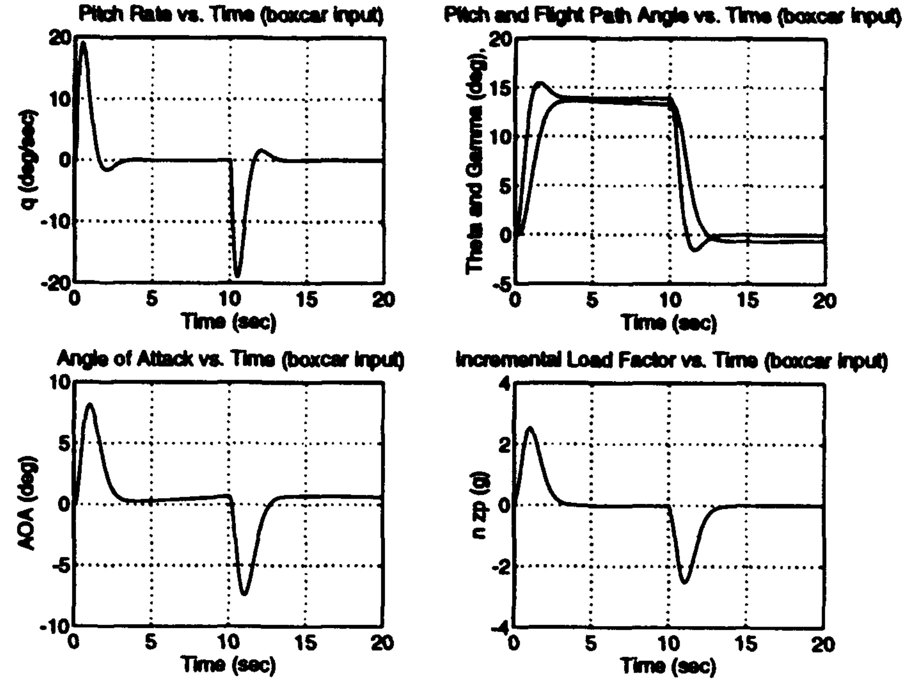

Figure E.38. HAVE GAS Configuration A1 Time Responses

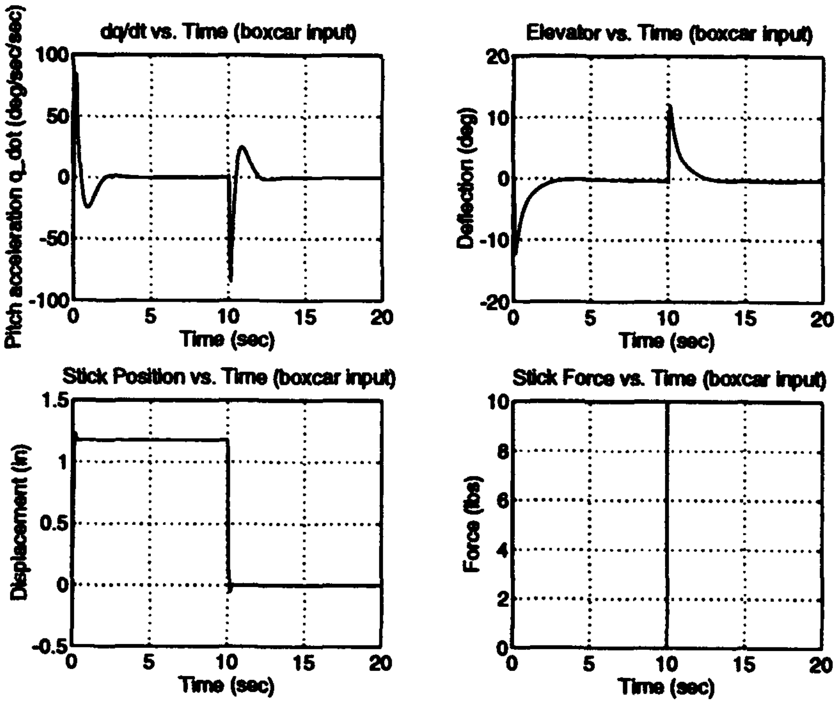

Figure E.39. HAVE GAS Configuration A1 Time Responses

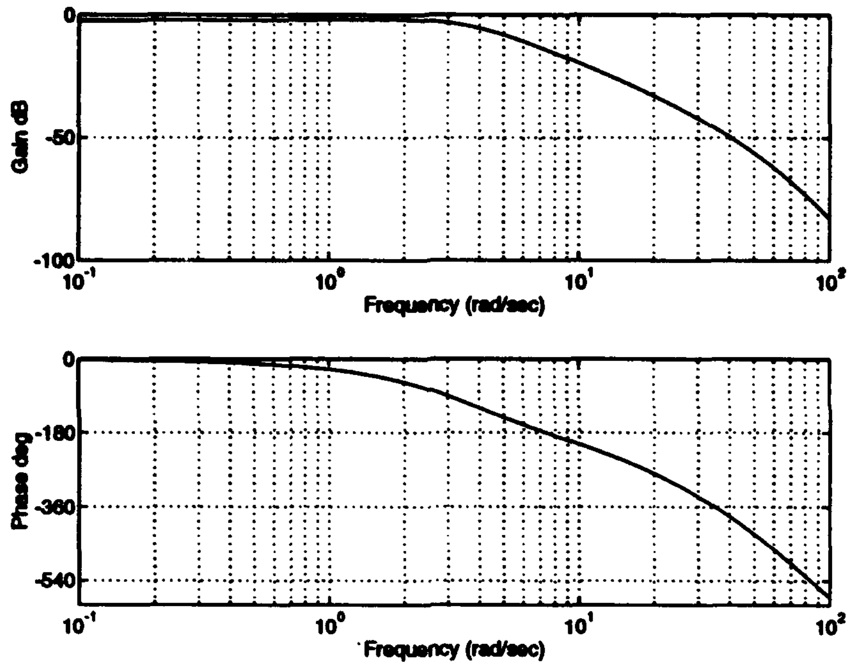

Figure E.40. HAVE GAS Configuration A2 θ/F_{es} Frequency Response

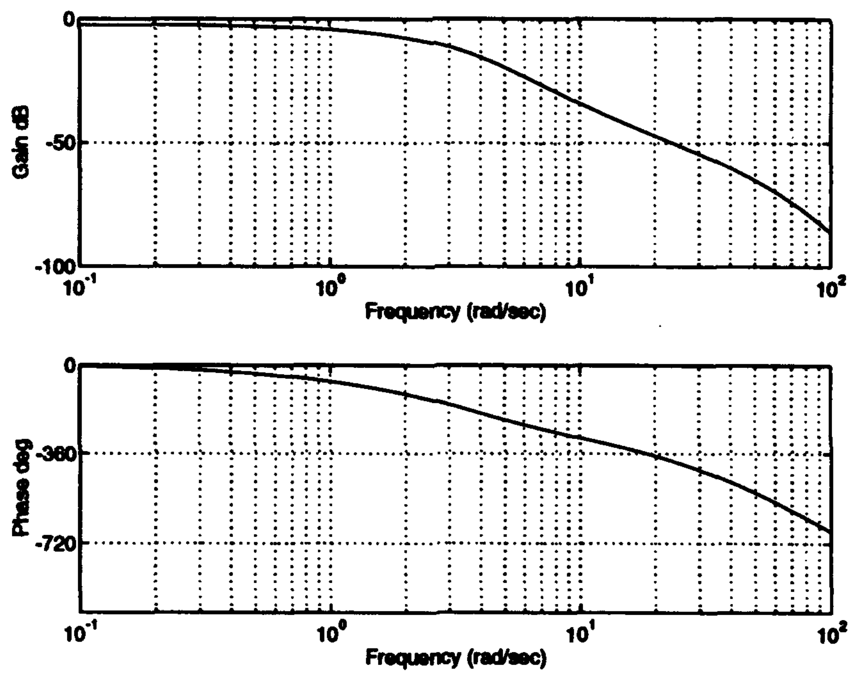

Figure E.41. HAVE GAS Configuration A2 γ/F_{es} Frequency Response

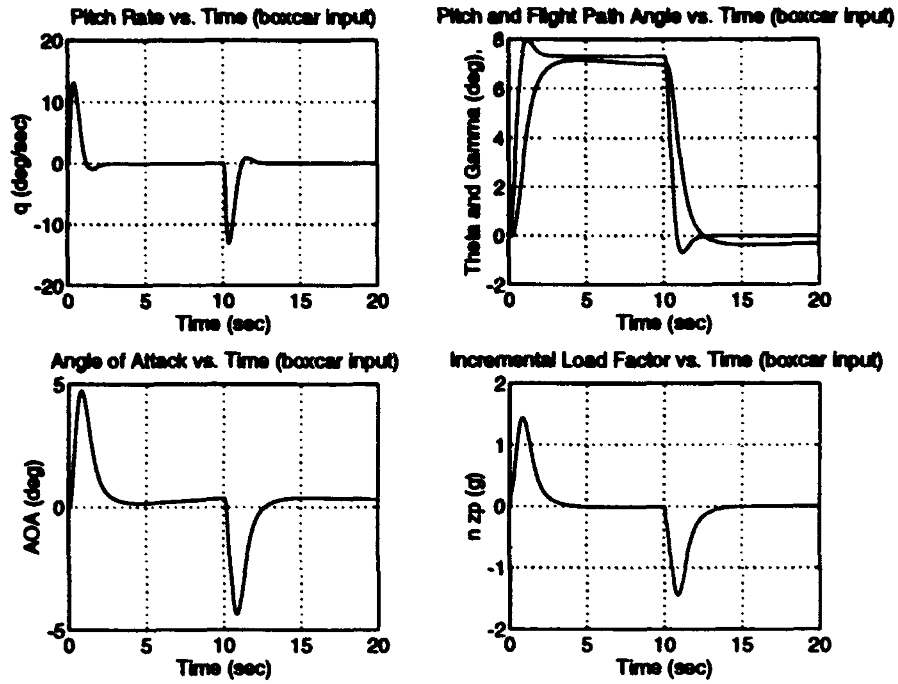

Figure E.42. HAVE GAS Configuration A2 Time Responses

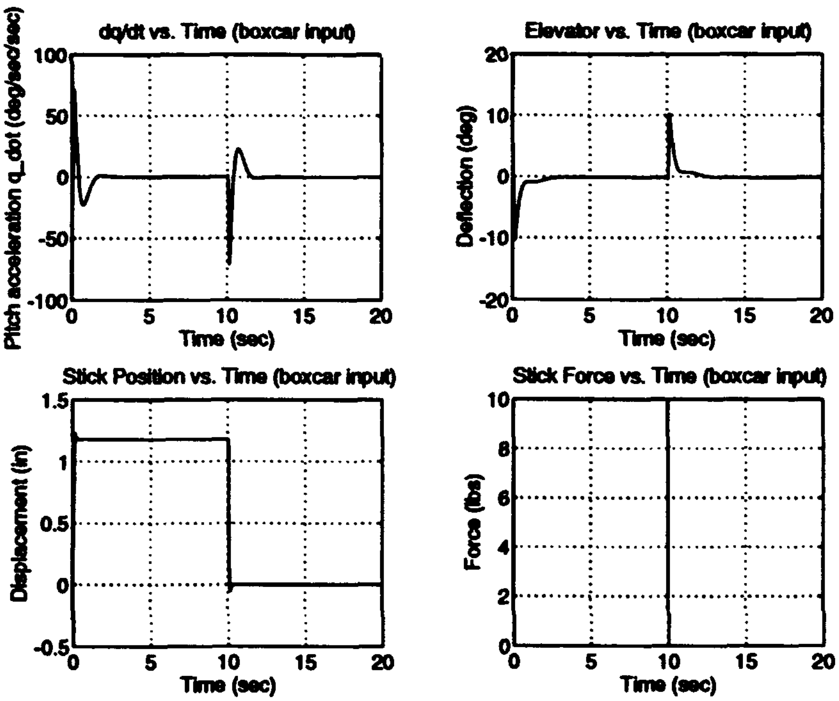

Figure E.43. HAVE GAS Configuration A2 Time Responses

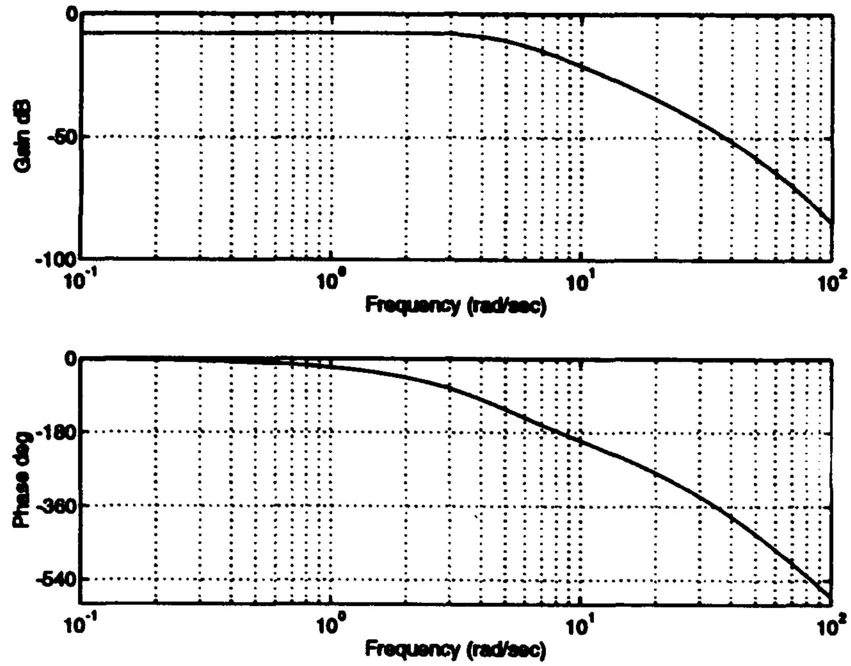

Figure E.44. HAVE GAS Configuration A3 θ/F_{es} Frequency Response

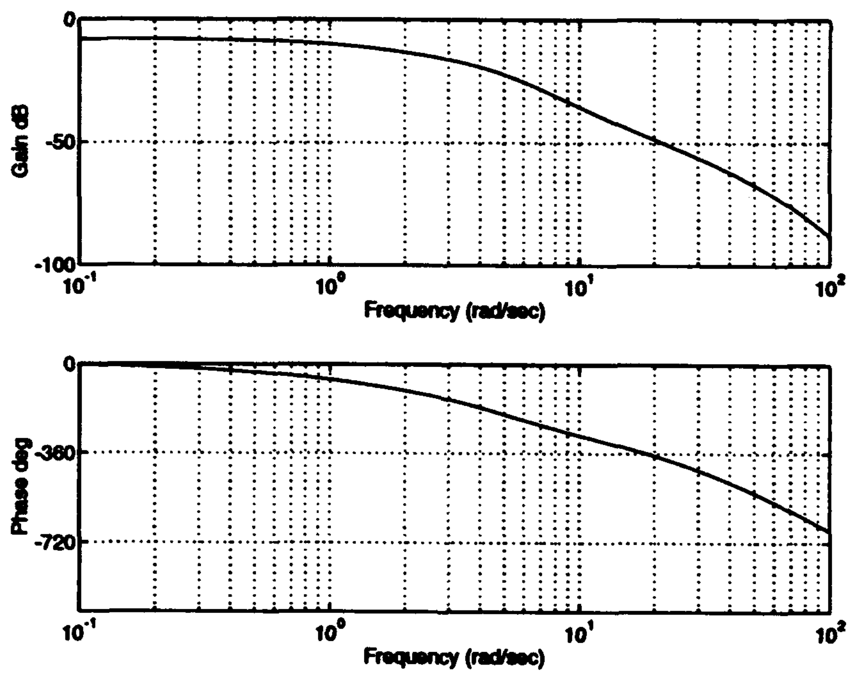

Figure E.45. HAVE GAS Configuration A3 γ/F_{es} Frequency Response

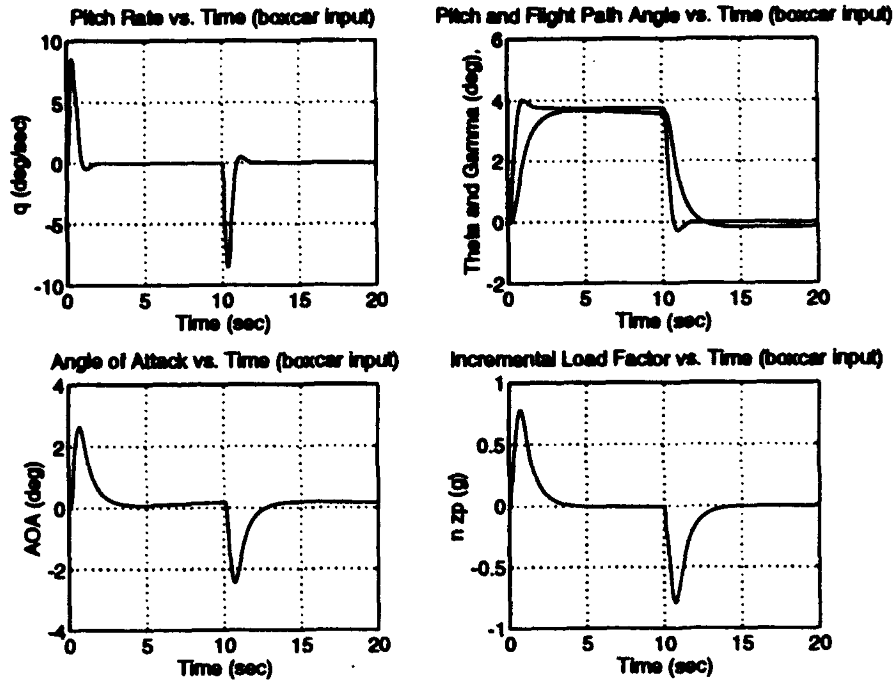

Figure E.46. HAVE GAS Configuration A3 Time Responses

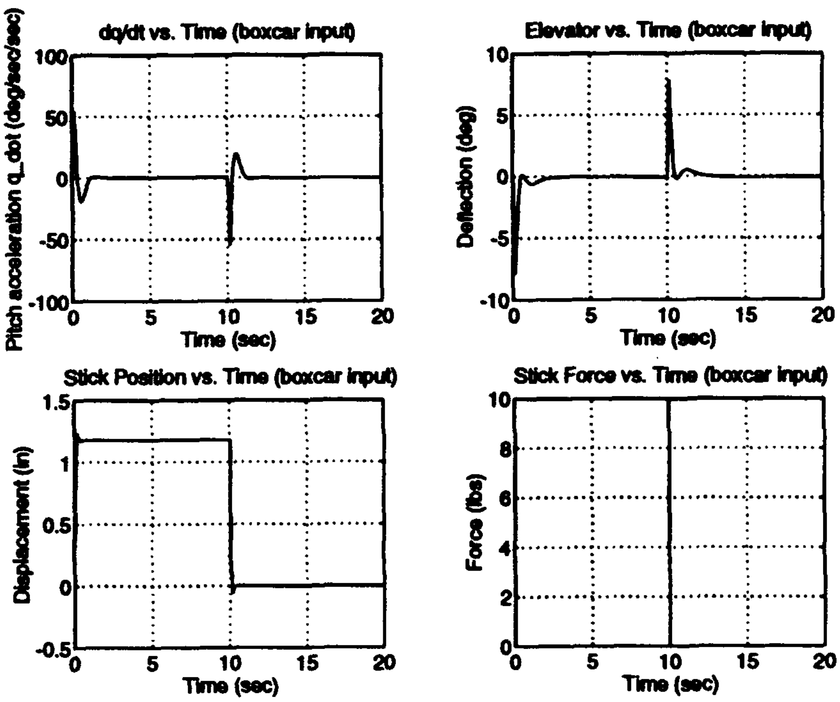

Figure E.47. HAVE GAS Configuration A3 Time Responses

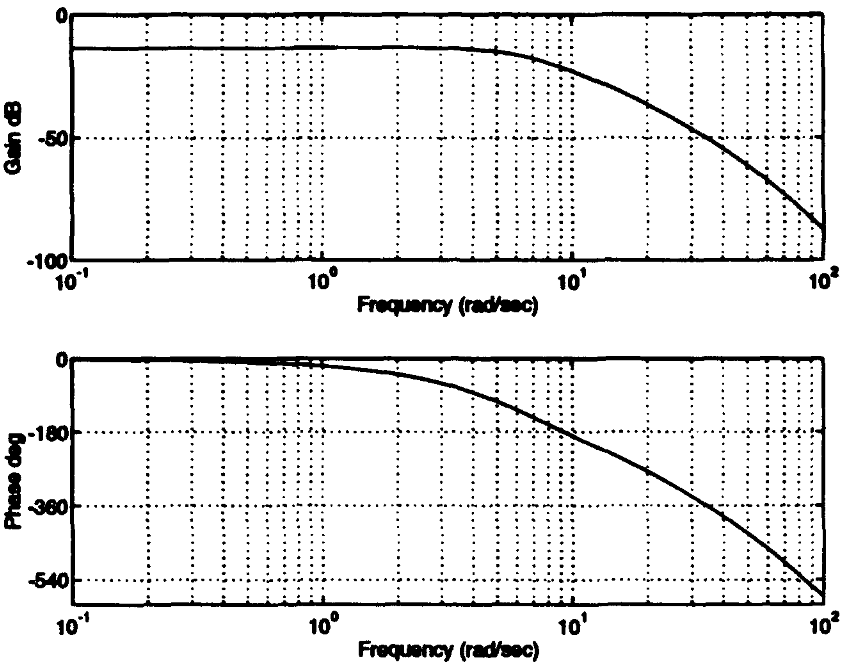

Figure E.48. HAVE GAS Configuration A4 θ/F_{es} Frequency Response

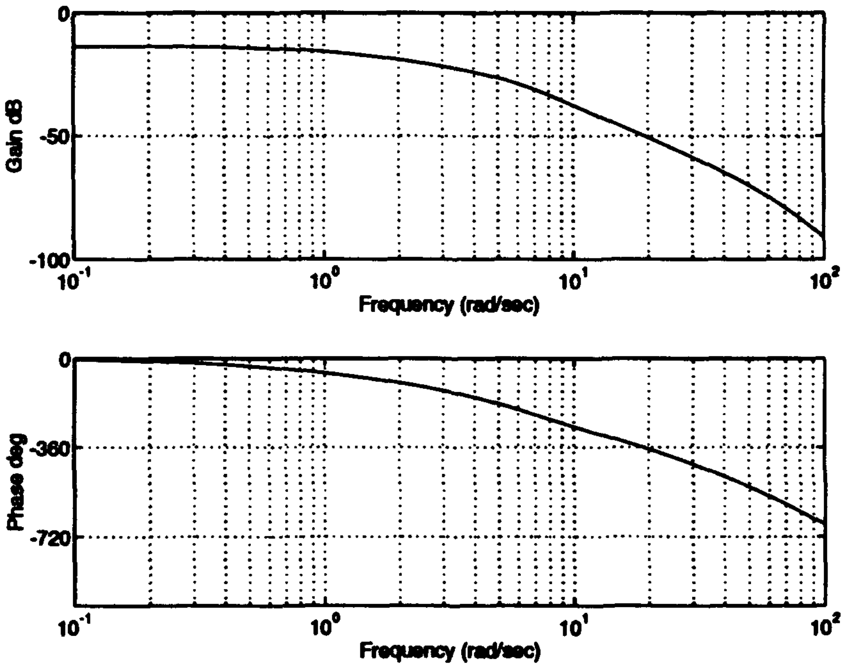

Figure E.49. HAVE GAS Configuration A4 γ/F_{es} Frequency Respon:

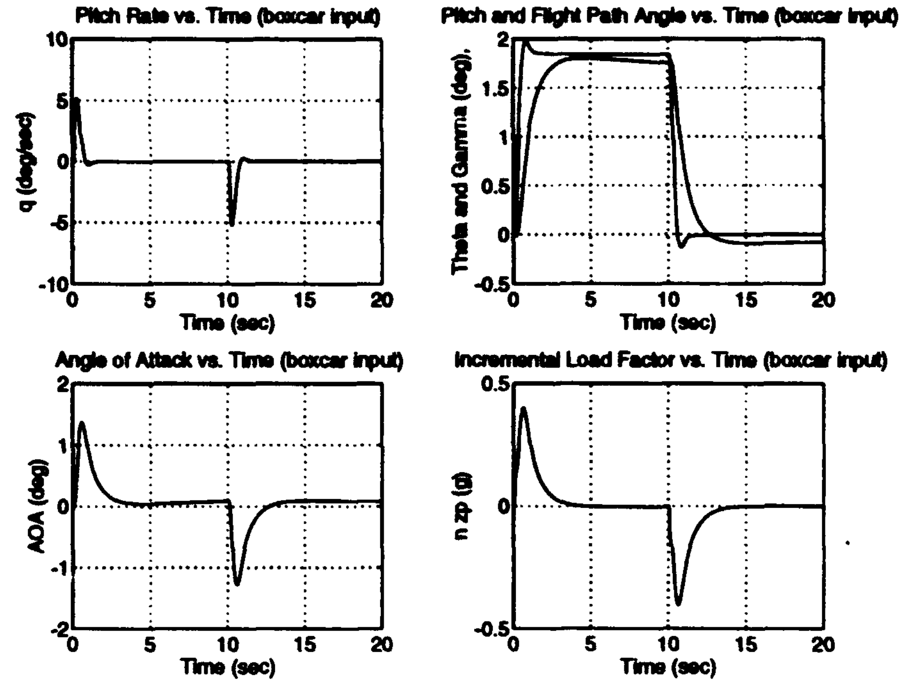

Figure E.50. HAVE GAS Configuration A4 Time Responses

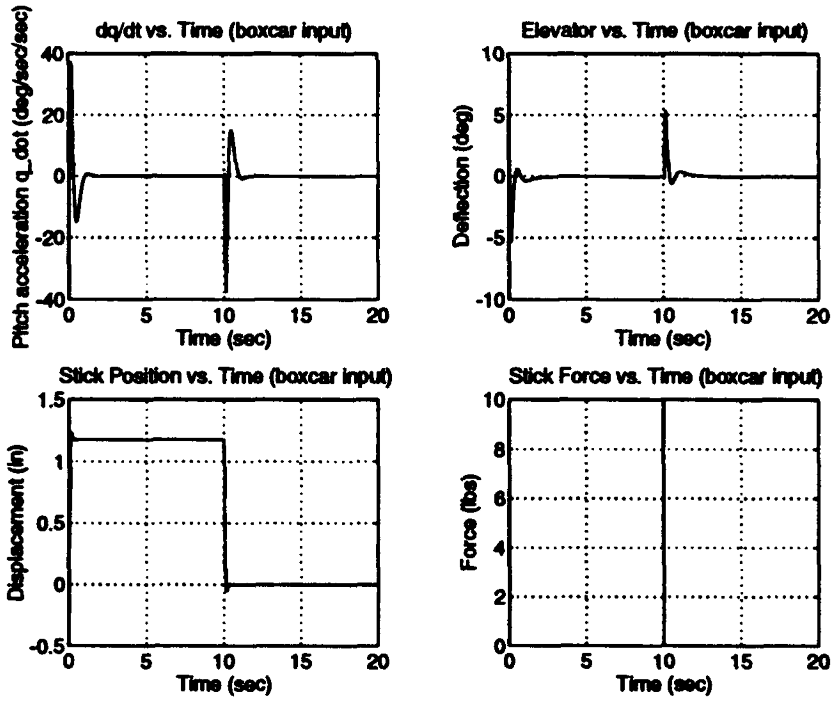

Figure E.51. HAVE GAS Configuration A4 Time Responses

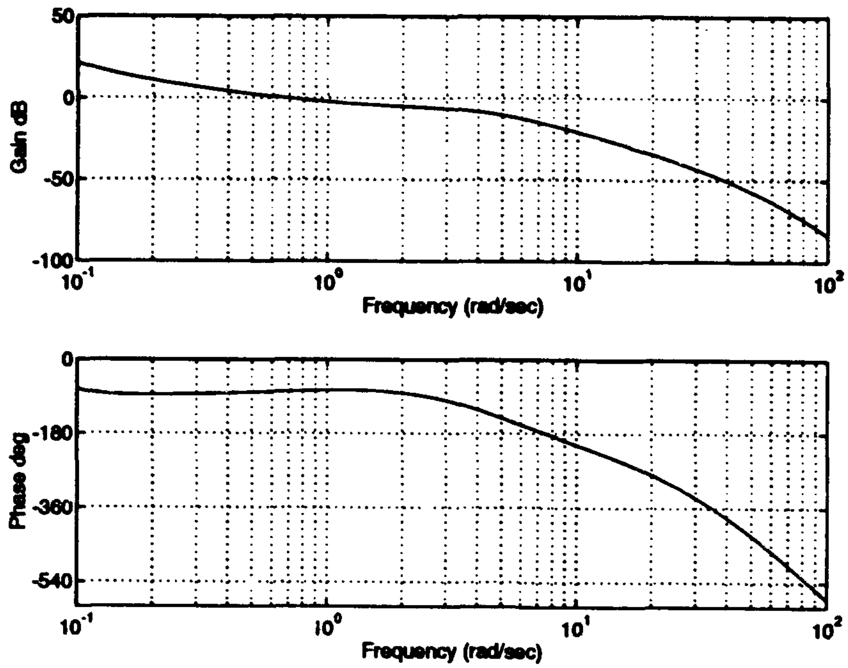

Figure E.52. HAVE GAS Configuration C1 θ/F_{es} Frequency Response

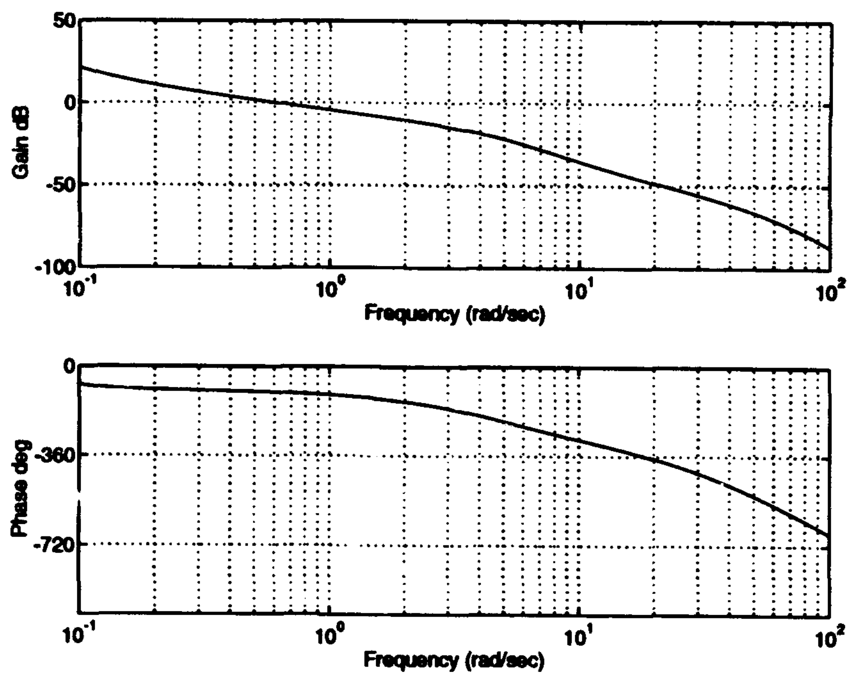

Figure E.53. HAVE GAS Configuration C1 γ/F_{es} Frequency Response

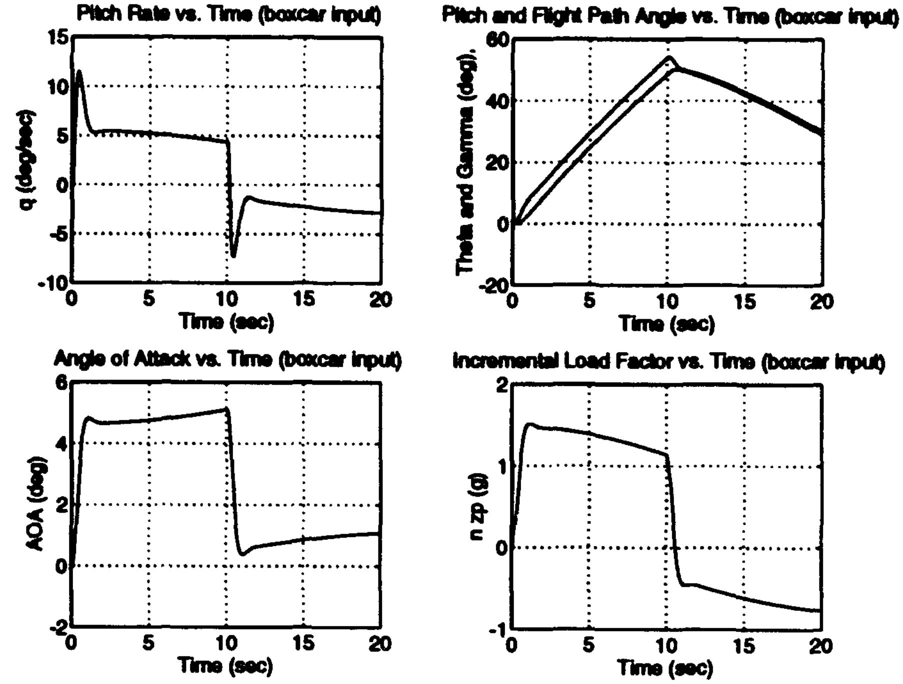

Figure E.54. HAVE GAS Configuration C1 Time Responses

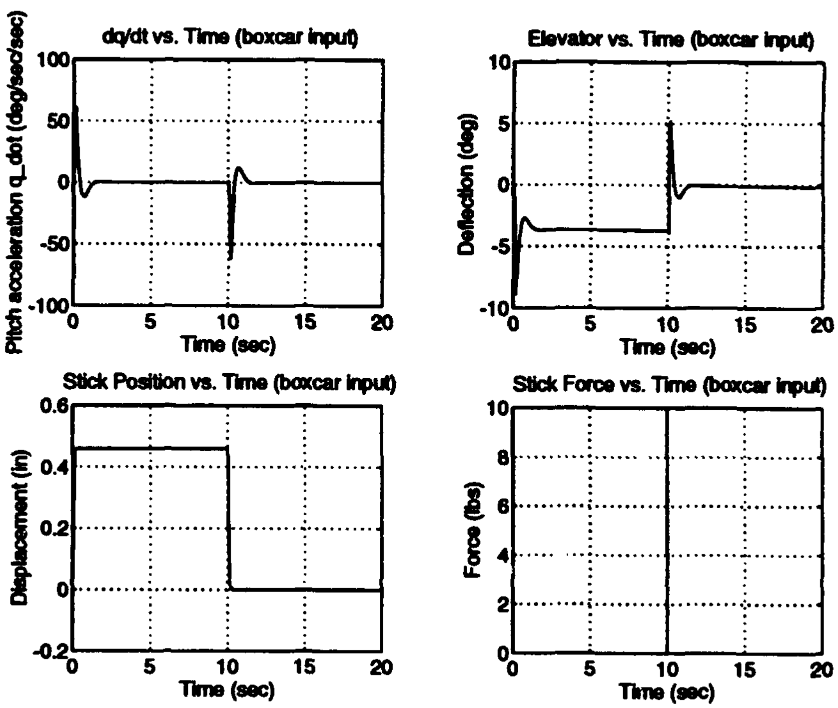

Figure E.55. HAVE GAS Configuration C1 Time Responses

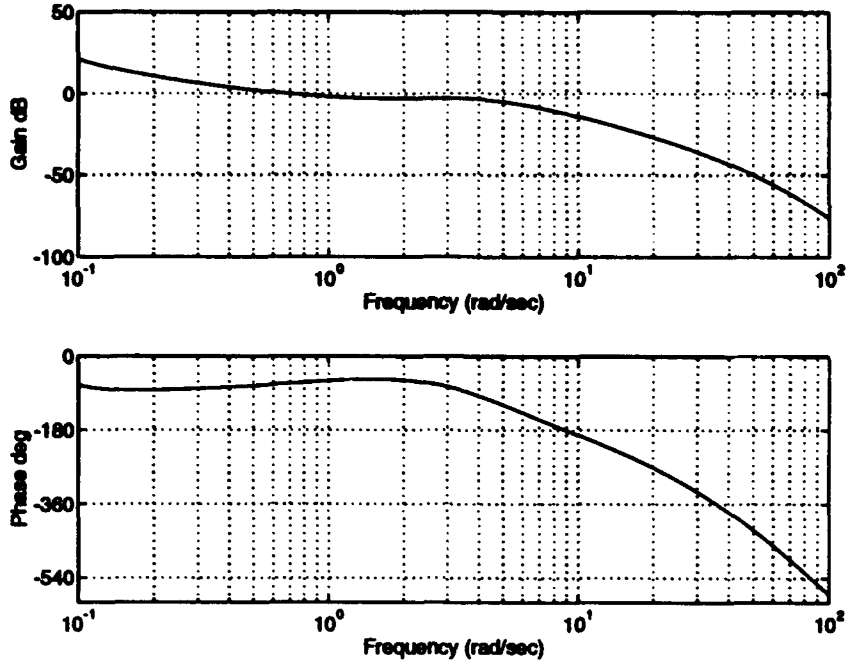

Figure E.56. HAVE GAS Configuration C1X θ/F_{es} Frequency Response

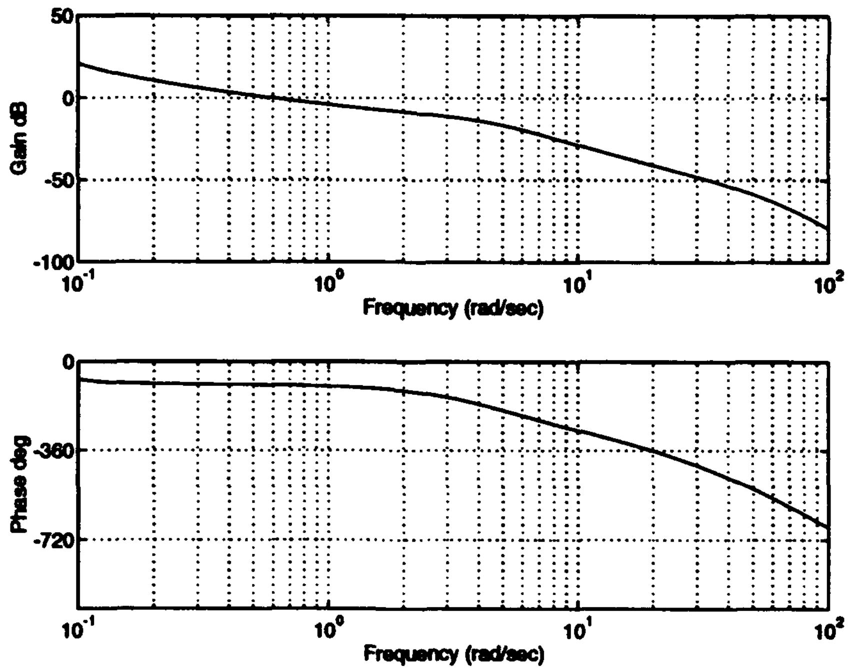

Figure E.57. HAVE GAS Configuration C1X γ/F_{es} Frequency Response

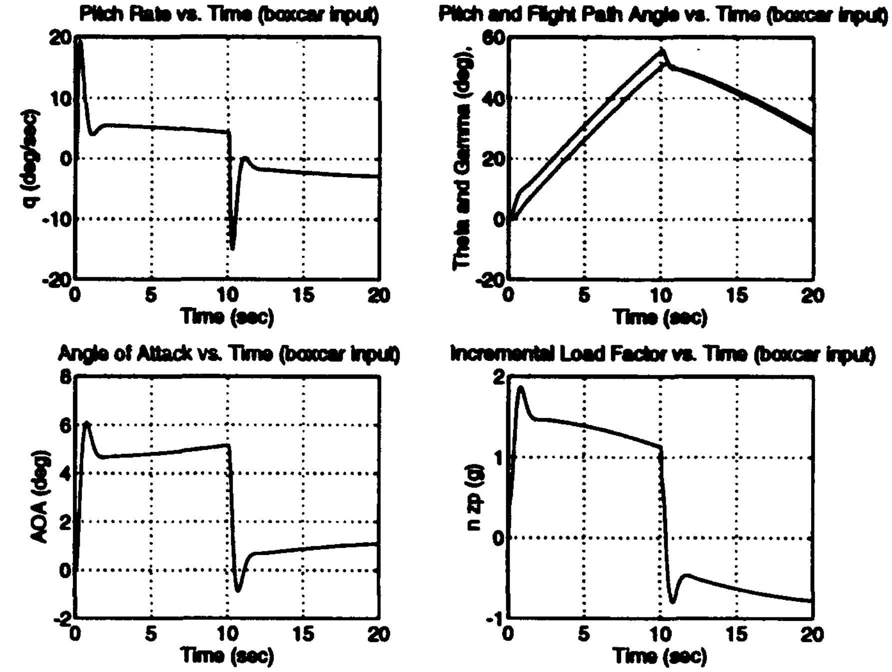

Figure E.58. HAVE GAS Configuration C1X Time Responses

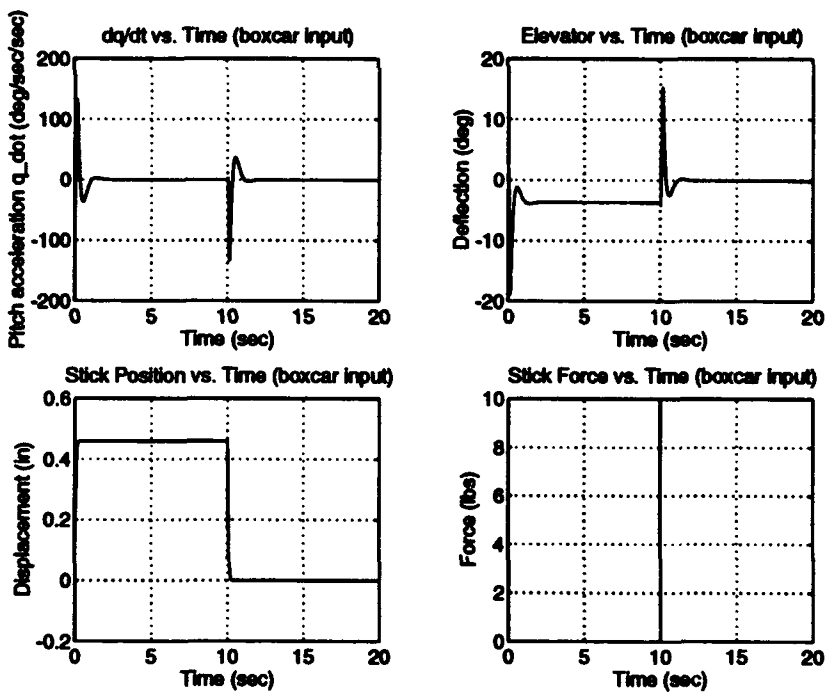

Figure E.59. HAVE GAS Configuration C1X Time Responses

E.6 Verification Time Histories for HAVE GAS Configurations

The following figures compare the step responses (10 lb input) for each HAVE GAS configuration with the Calspan offline simulator step responses. The Calspan offline simulator was essentially identical to the SIMULINK model(s) described in this Appendix. The time histories for configuration C1X (Figure E.73) reflect a command gain lower than was actually used during blind evaluations.

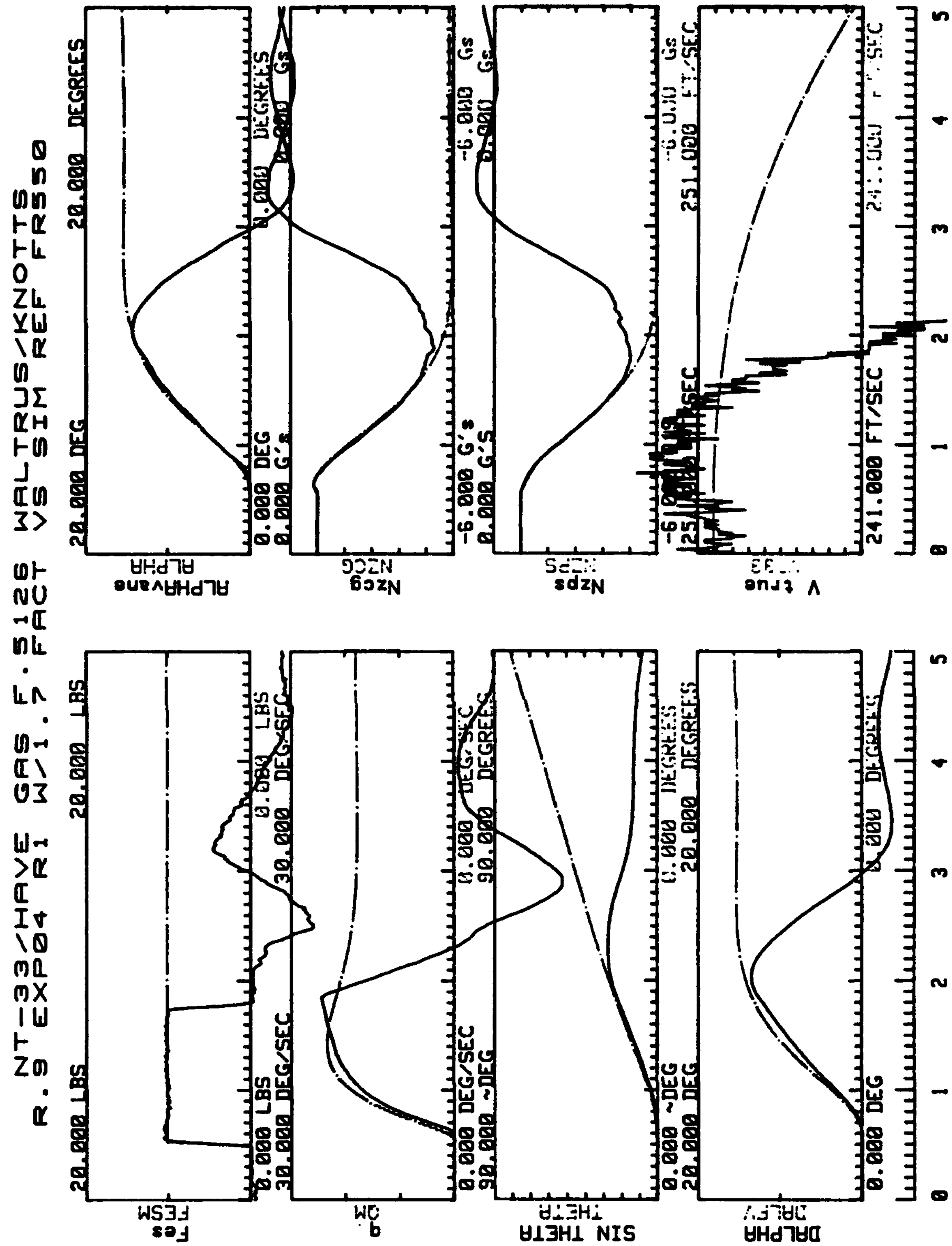

Figure E.60. HAVE GAS Configuration R1 Verification

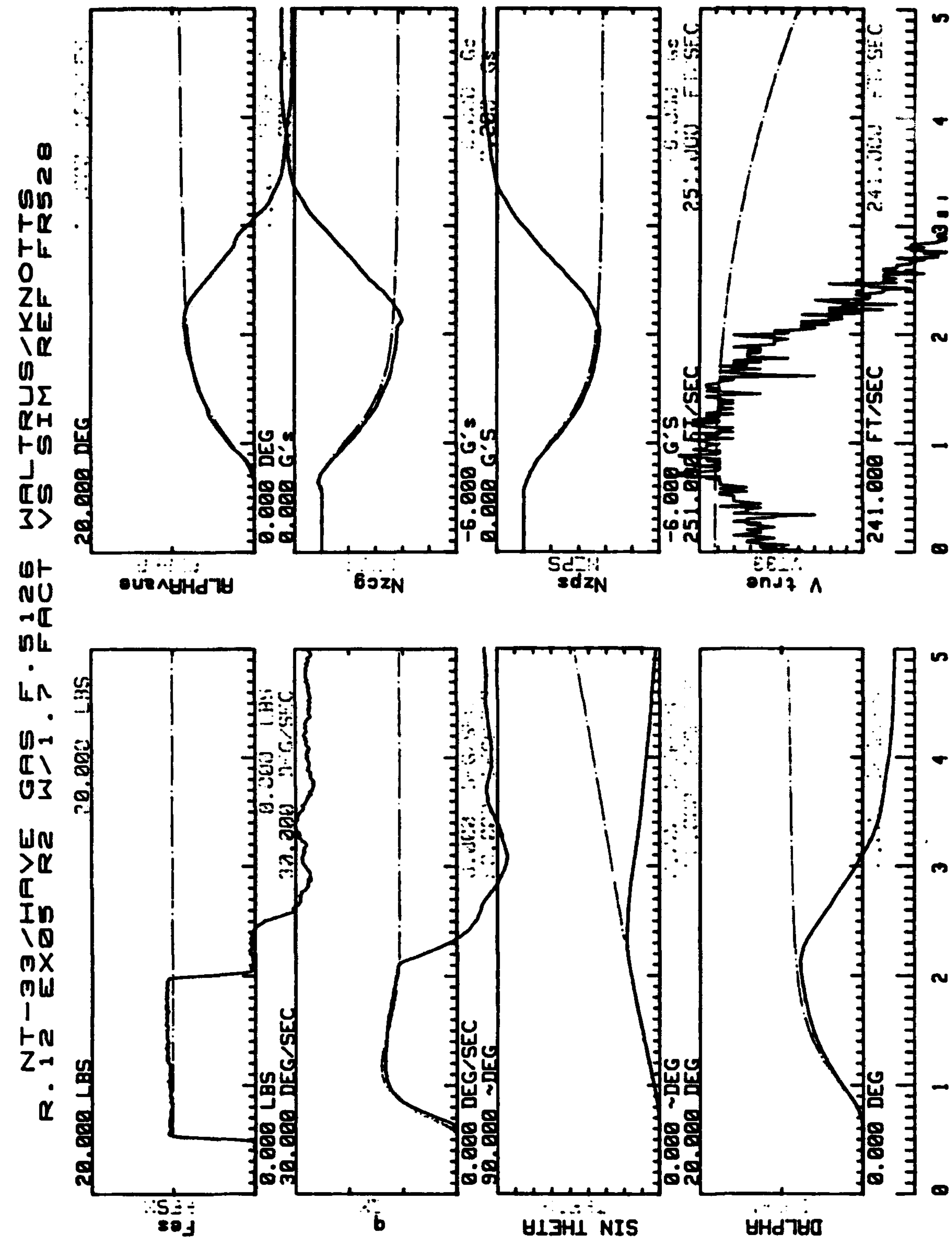

Figure E.61. HAVE GAS Configuration R2 Verification

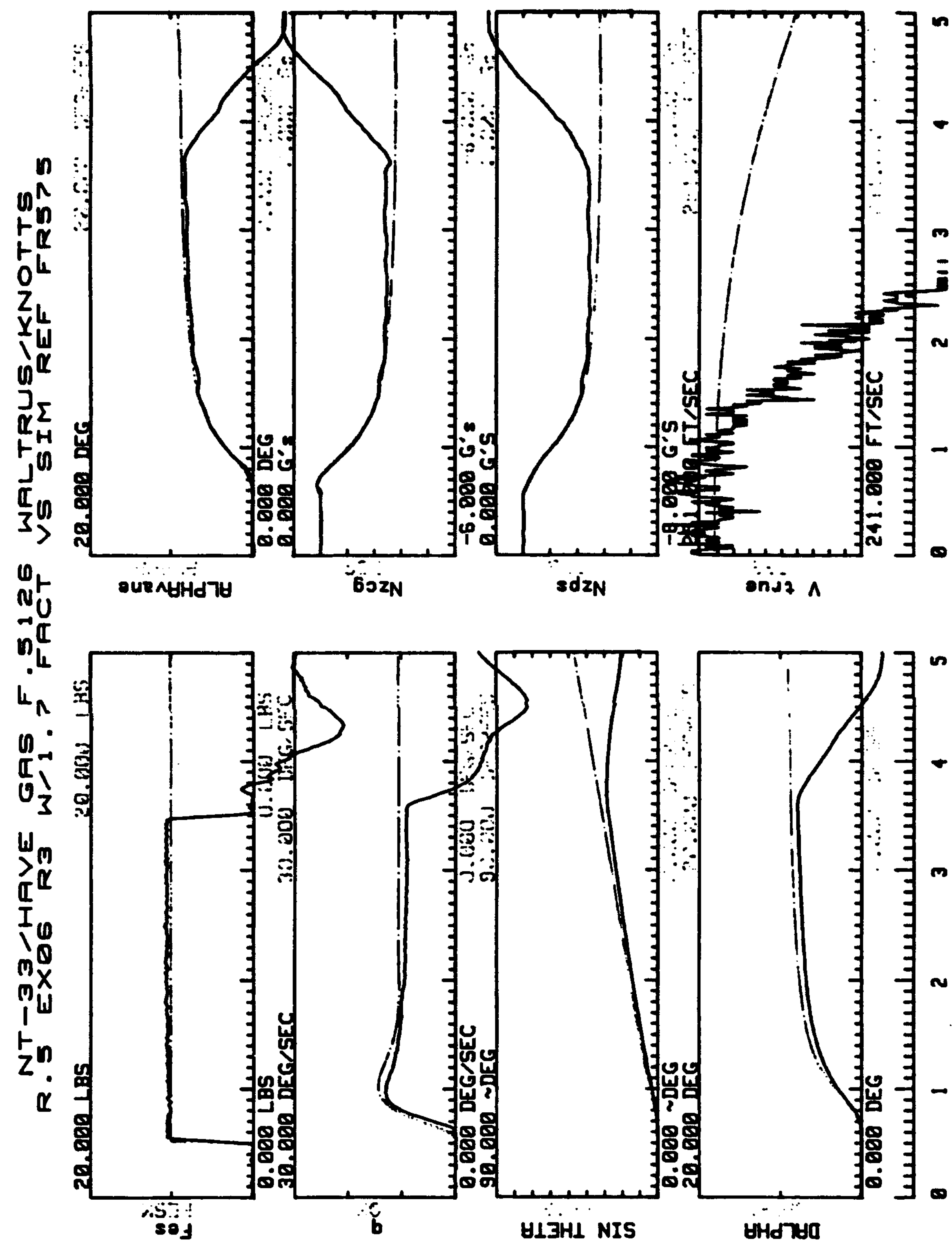

Figure E.62. HAVE GAS Configuration R3 Verification

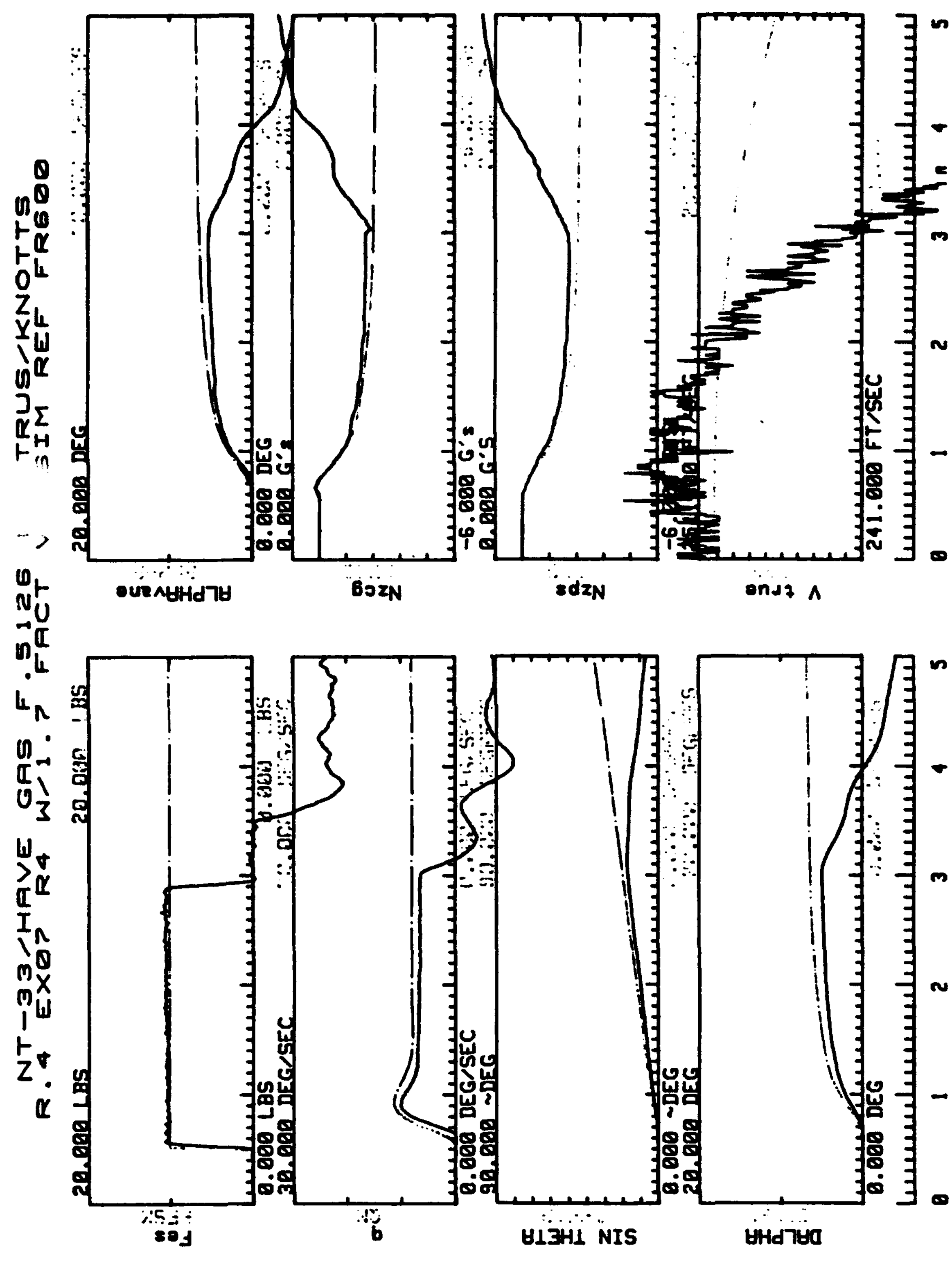

Figure E.63. HAVE GAS Configuration R4 Verification

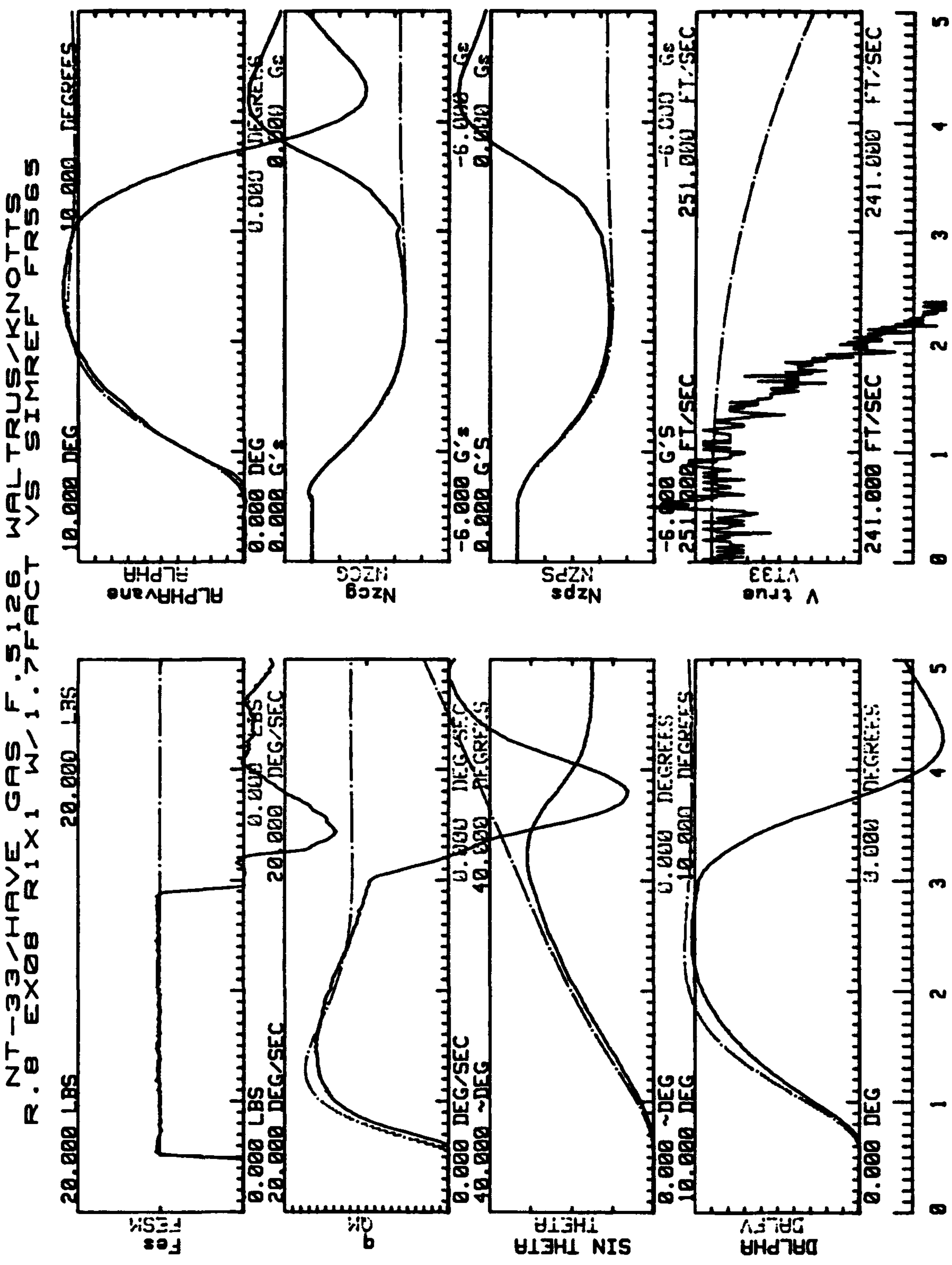

Figure E.64. HAVE GAS Configuration R1X Verification

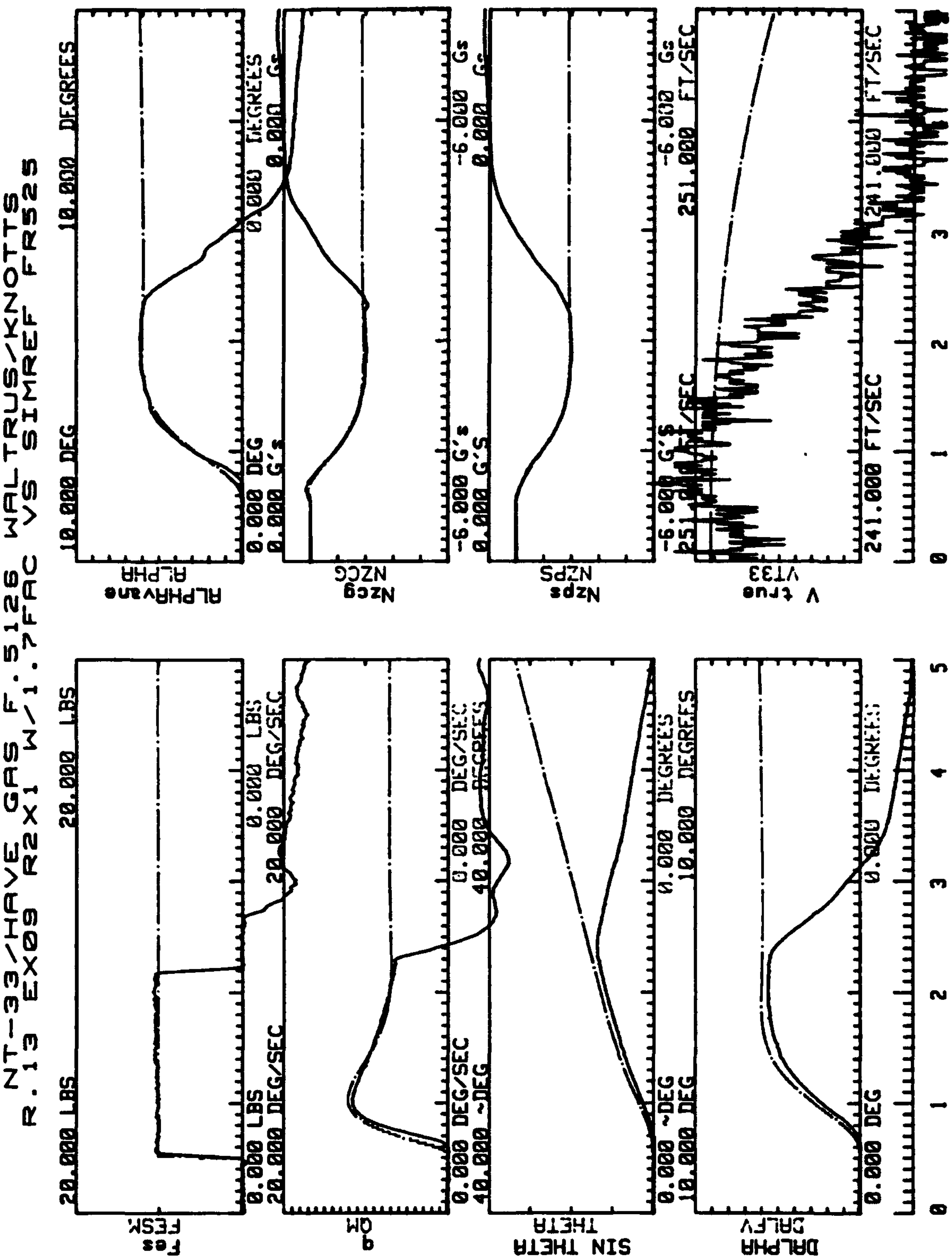

Figure E.65. HAVE GAS Configuration R2X Verification

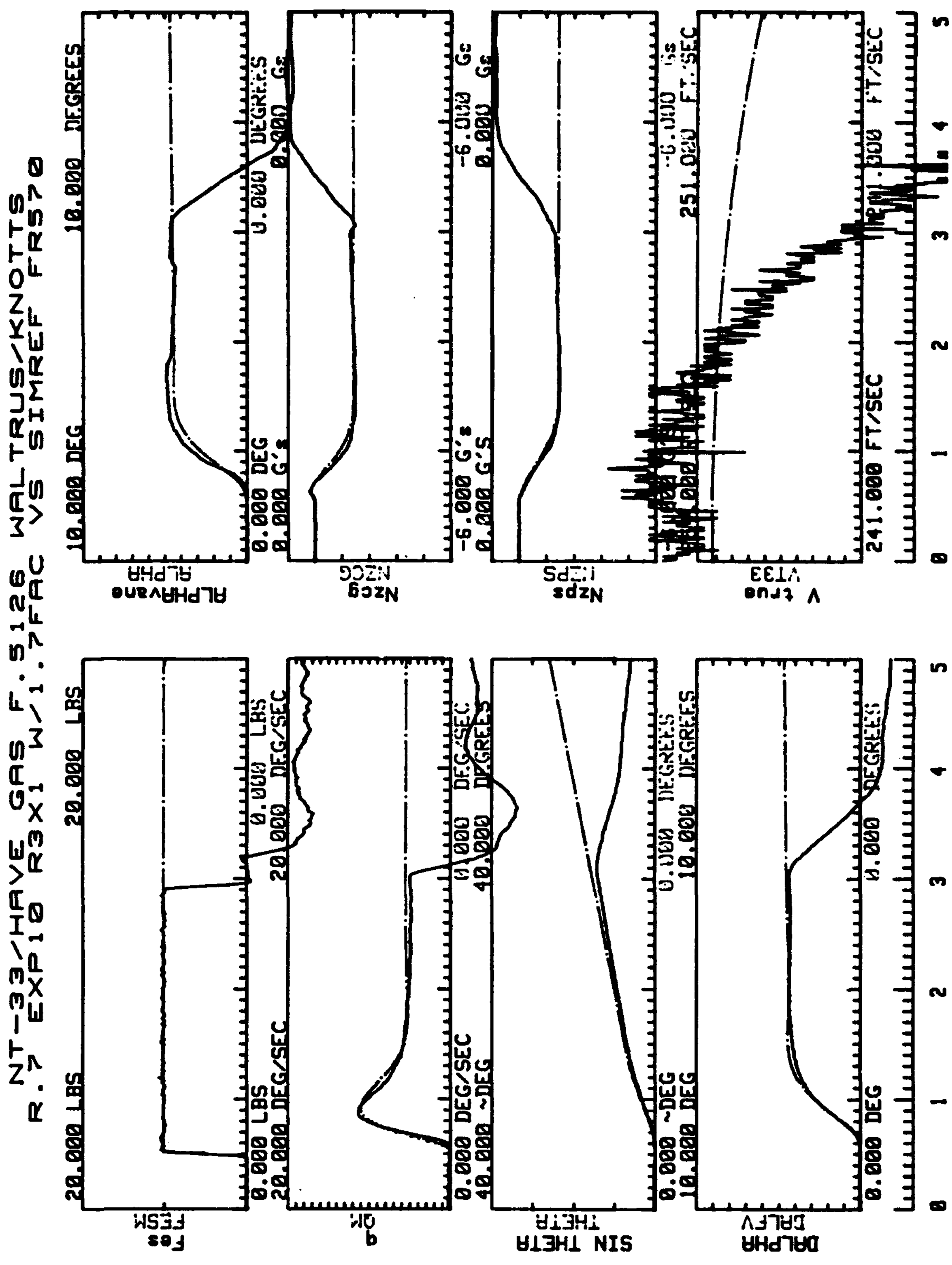

Figure E.66. HAVE GAS Configuration R3X Verification

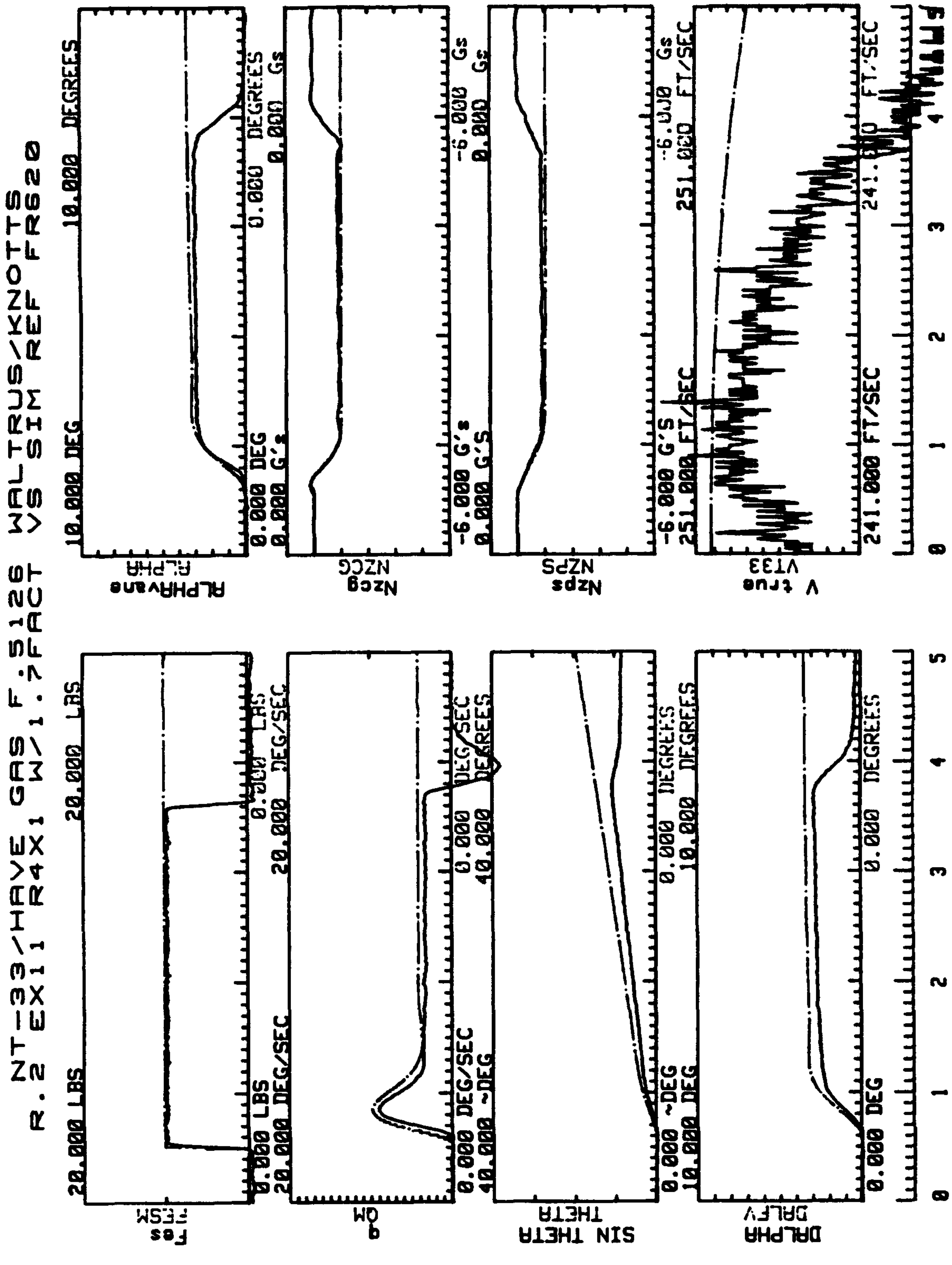

Figure E.67. HAVE GAS Configuration R4X Verification

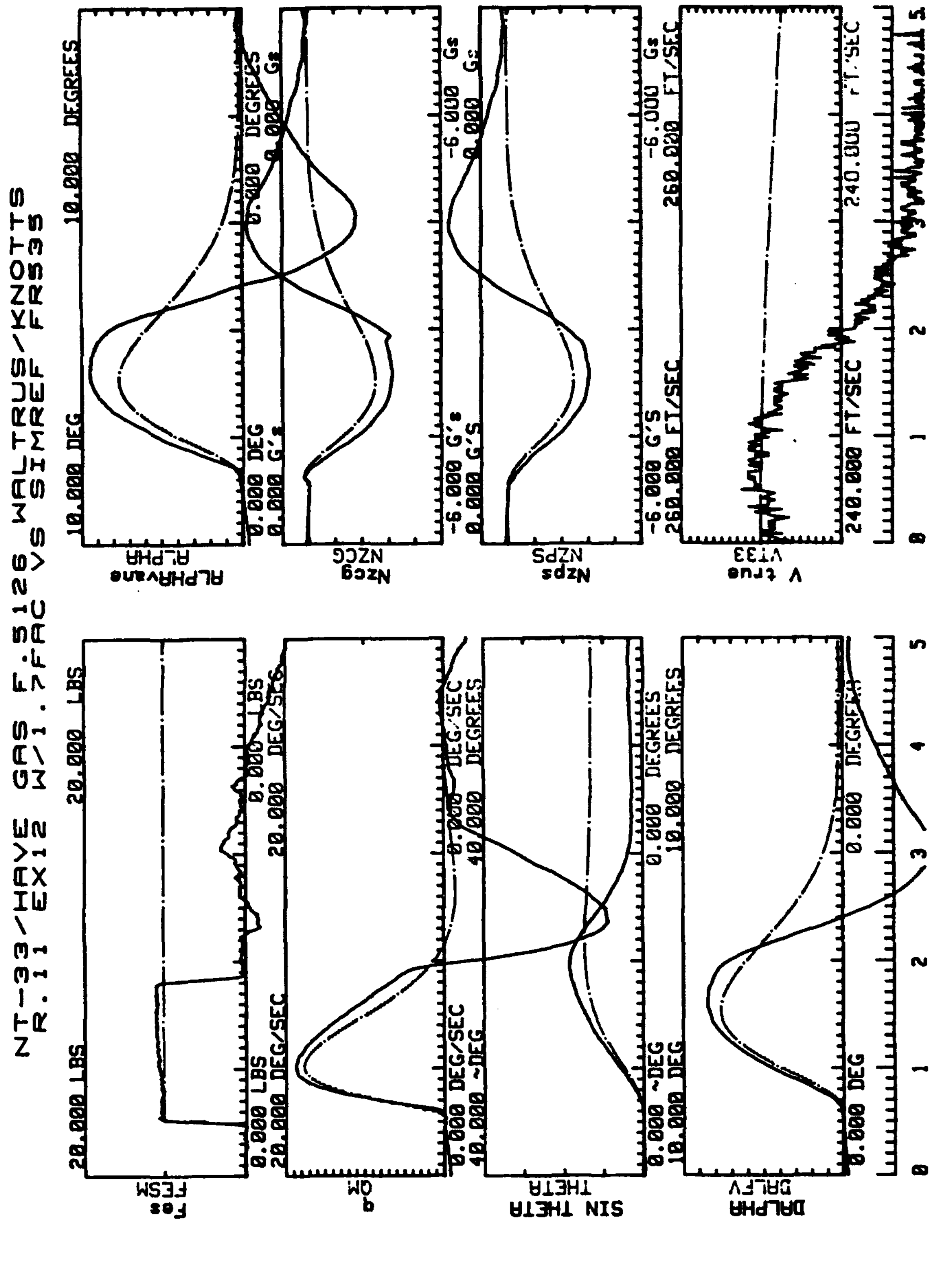

Figure E.68. HAVE GAS Configuration A1 Verification

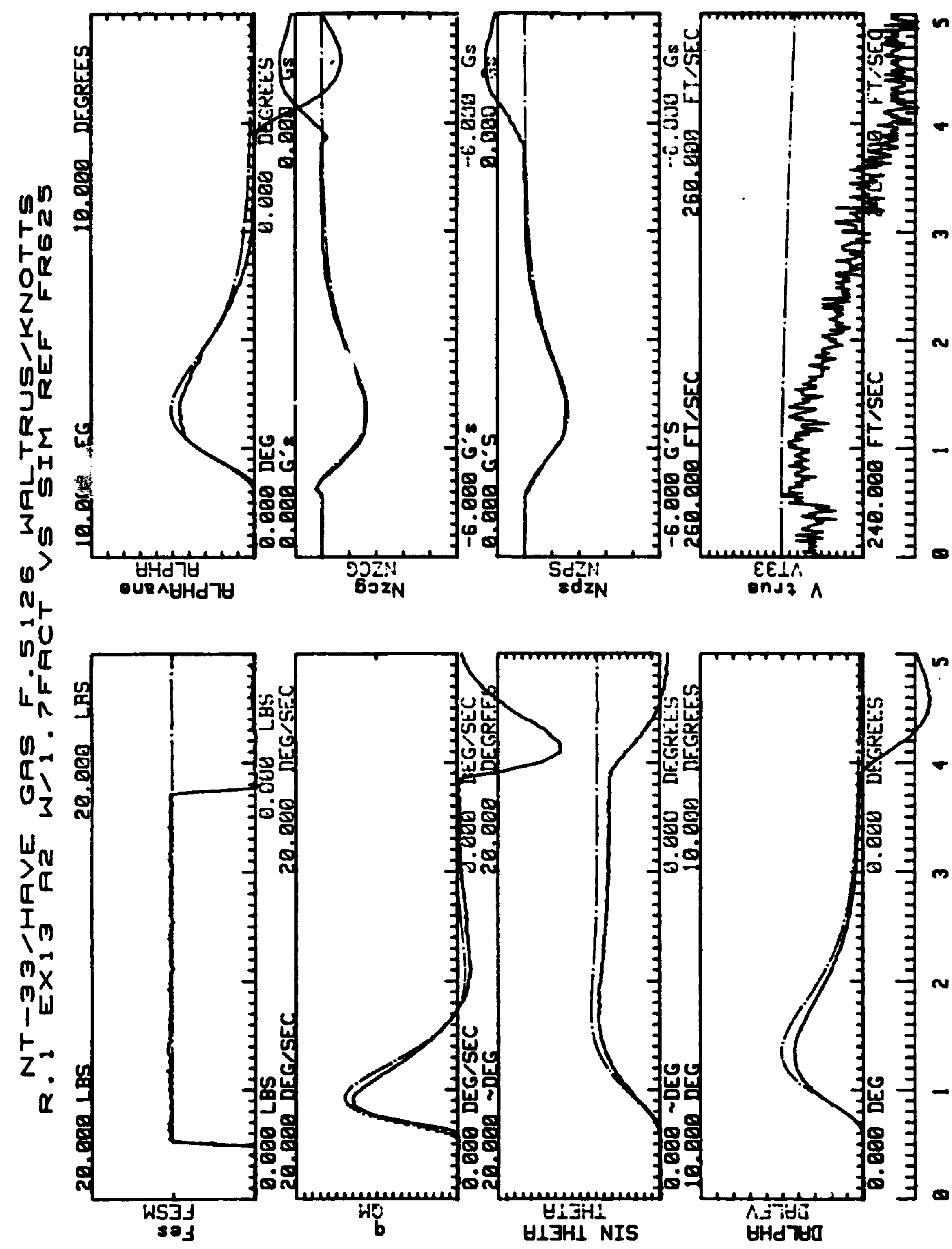

Figure E.69. HAVE GAS Configuration A2 Verification

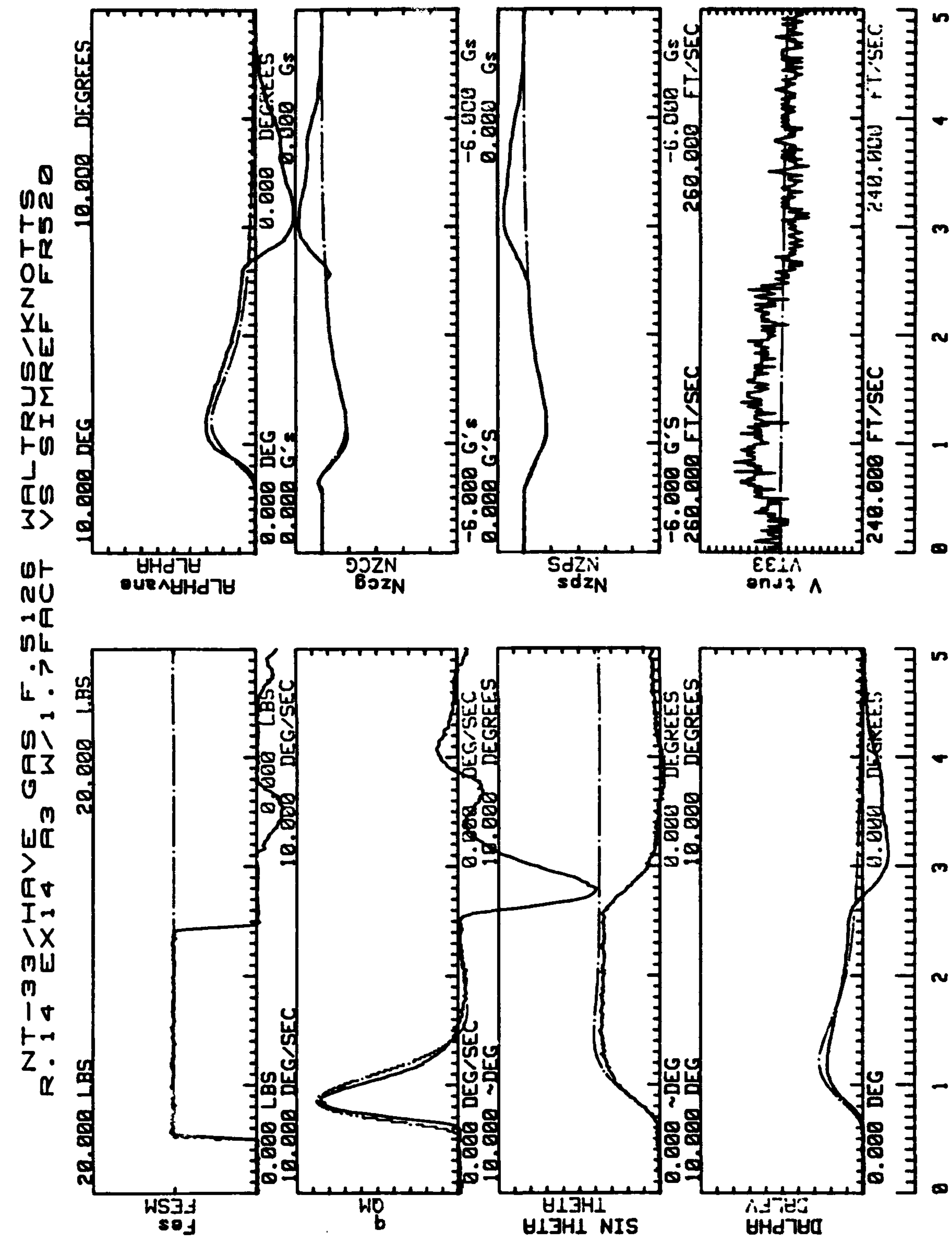

Figure E.70. HAVE GAS Configuration A3 Verification

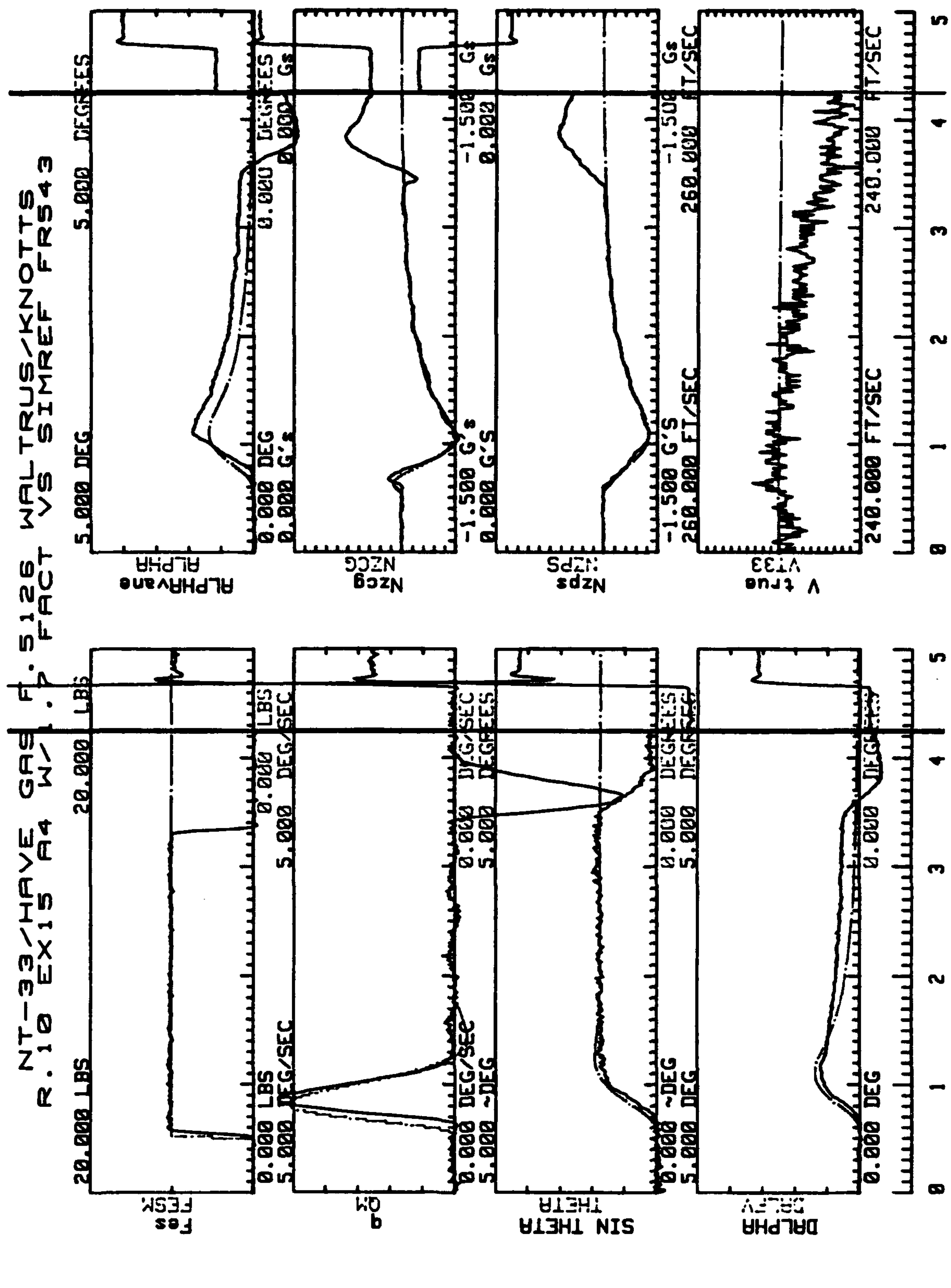

Figure E.71. HAVE GAS Configuration A4 Verification

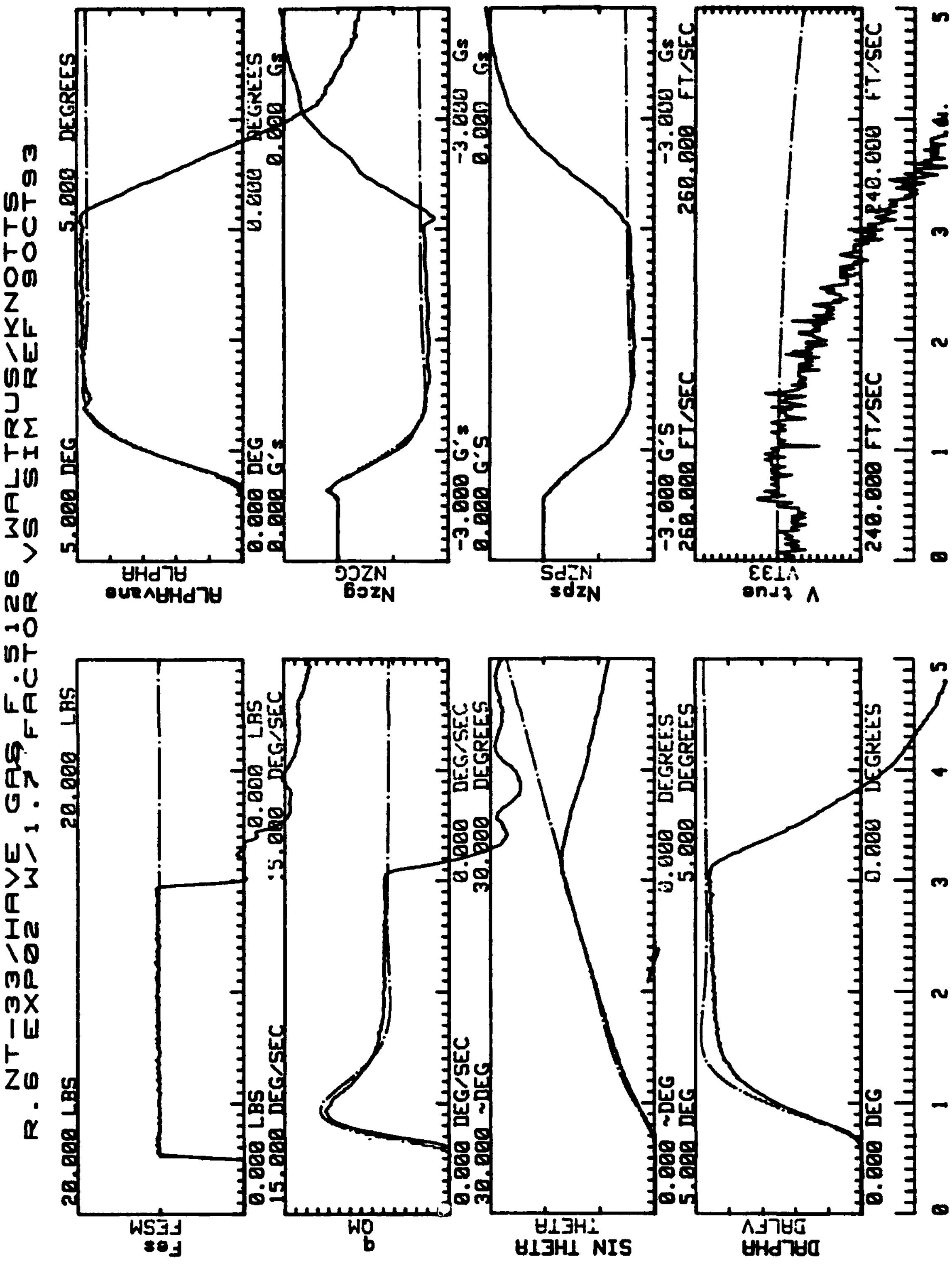

Figure E.72. HAVE GAS Configuration C1 Verification

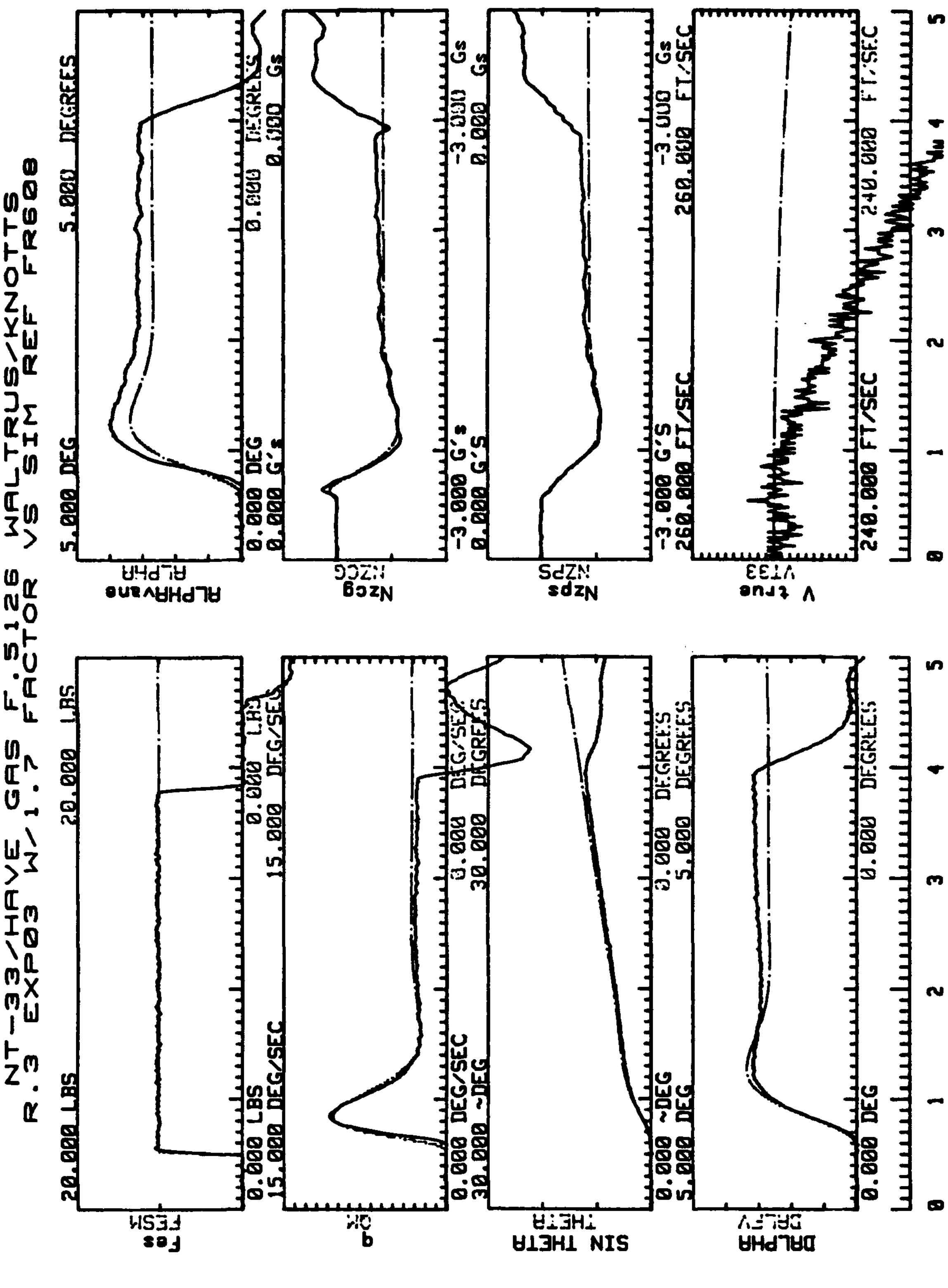

Figure E.73. HAVE GAS Configuration C1X Verification

Appendix F. *HAVE GAS Pilot Commentary*

F.1 Evaluation Flight Summary

Eight evaluation sorties were flown at Patuxent River NAS, MD from 9 to 11 Oct 93. Table F.1 list the flight times and aircrews for the evaluation sorties.

Table F.1. Evaluation Flight Summary

Evaluation Flight Summary						
Eval Flight	NT-33A Flight	Evaluation Pilot	Safety Pilot	Flight Time	S-3A Pilots	S-3A Aircrew
1	5126	Watrous	Peer	1.6	Fitzgerald, Summers	Barth, Meyer
2	5127	Taschner	Peer	1.5	Fitzgerald, Summers	Barth, Meyer
3	5128	Watrous	Peer	1.6	Andreas, Wright	—
4	5129	Taschner	Peer	1.6	Griffith, Rauch	Hoy, Mattedi
5	5130	Watrous	Peer	1.5	Griffith, Rauch	Hoy, Mattedi
6	5131	Taschner	Knotts	1.5	Griffith, Rauch	Hoy, Mattedi
7	5132	Watrous	Knotts	1.6	Andreas, Hill	Kipp
8	5133	Taschner	Knotts	1.6	Andreas, Hill	Wilcox

F.2 Pilot Commentary

The pilot commentary from the fifty eight blind evaluations were transcribed from the HUD video tapes (voice cassette tape for the first flight) and are recorded on the following pages.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R1	2	18	A	3	6	6	4	A

I. Pilot Rating (Cooper-Harper Scale)
Desired performance was achieved. The fact that we got desirable was almost luck than any thing else. There were deficiencies that definitely warranted improvement. Even though desired performance was achieved, there was considerable compensation that was going on to make that happen. I'm between a 5 and a 6 here. As far as moderately objectionable, I'd say they're very objectionable. I wouldn't want to have to fly this kind of airplane. I'll go with a rating of six. Extensive compensation is required. It's very easy to get into a bobble.

II. Pitch Control During Approach to Basket

a) Undesirable motions? Any attempt to get close to the basket, I start to feel like I'm getting into a PIO. There's very undesirable motions.

b) Predictability? Initial response was unpredictable. Even back here far in trail with the tanker, I put an input in and the response - it's kind of slow and then happens. I can tell with little inputs, the response feels abrupt. It's very easy to get out of phase with it and get into some bobbling.

c) Initial response: too quick / too slow?

d) Does aggressiveness affect handling qualities? Aggressiveness definitely affected the handling qualities.

e) Are you having to compensate? I very definitely had to compensate. I was holding the stick tighter and forcing myself to make very small corrections. I learned very quickly I had to be lined up with the drogue with no flight path changes necessary in the end game. Talk about grabbing the stick tighter and stuff like that, I'm definitely doing that. I have to spend a lot of time looking at the S-3 and trying to dampen out my inputs cause it's very easy to get a bobble, an unwanted bobble going. I don't like this one at all.

III. Feel System

a) Forces: too high / too low? Forces were fine.

b) Stick deflection: too much / too little? Stick deflection was - that was OK.

IV. PIO Tendency Rating
Just entering the control loop didn't cause a divergent oscillation, but when I attempted to get aggressive and exert tight control, there was very definitely oscillations. It got to an amplitude, I didn't feel like it was going to run away. But we definitely got into some sustained oscillations. I'm going to go with a four. A PIO rating of four.

V. Turbulence Rating
Turbulence wasn't a factor. Turbulence level alpha.

VI. Drogue Stable?
Drogue was stable.

VII. Want to change your C-H rating? No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R1	6	32	A	3	4	7	4	B

I. Pilot Rating (Cooper-Harper Scale)
Yes, it was controllable. Adequate performance was attainable - the workload was fairly high. I would say deficiencies require improvement on this one. They're very objectionable. There was extensive pilot compensation. It's a tough call between a six and seven. Controllability I didn't think was an issue in the whole thing. I would say that I was more along the lines of maximum tolerable workload almost though. I would want it improved. I wouldn't want to fly the airplane. I'm going to go with major deficiencies. Seven.

II. Pitch Control During Approach to Basket

a) Undesirable motions? There was an up and down feeling of acceleration and flight path change and predictably it got worse as you tried to tighten up and get more precise.

b) Predictability? No where near the precision that you would desire. It's very hard to be precise.

c) Initial response: too quick / too slow? Definitely the airplane is too pitch sensitive. You can feel accelerations - a tendency for a PIO type situation. Even after hooking up, I still have those same feelings.

d) Does aggressiveness affect handling qualities? Aggressiveness definitely affected the handling qualities and they would deteriorate.

e) Are you having to compensate? I was having to compensate by very lightly gripping the stick. Spending a lot of time looking at the S-3, and keeping the basket in my peripheral vision. There's a lot of pilot compensation that has to go on to keep your inputs very small. It requires extremely small inputs, very, very small.

III. Feel System

a) Forces: too high / too low? Stick forces were too light.

b) Stick deflection: too much / too little? I couldn't move the stick very much at all before I had undesirable motion going on.

IV. PIO Tendency Rating
There was definitely oscillations when you tightened up your control. I wouldn't say they were divergent, they were limited but they were very unwanted. Tendency for a PIO to develop easily. PIO rating of 4.

V. Turbulence Rating
I'd say bravo.

VI. Drogue Stable?
Drogue was relatively stable.

VII. Want to change your C-H rating? No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R1	8	04	A	3	5	7	4	C

I. Pilot Rating (Cooper-Harper Scale)
Is the airplane controllable - yes. Is adequate performance attainable with a tolerable pilot workload - I'd say that this one deficiencies require improvement. They don't just warrant it - it requires it. They were major deficiencies. The compensation I'd say was between considerable and intense. I think I can control the airplane. I'll go with a seven again. Controllability wasn't in question, but performing the task requires maximum tolerable pilot compensation. Cooper-Harper rating of seven. Primary problem was an unpredictability in the initial response. Easy tendency to PIO.

II. Pitch Control During Approach to Basket

a) Undesirable motions? There were undesirable motions. You could feel accelerations and pitching motions that were very undesirable for very small movements of the stick.

b) Predictability? Predictability was poor.

c) Initial response: too quick / too slow? Primary problem was an unpredictable initial response. Initial response was too quick.

d) Does aggressiveness affect handling qualities? Aggressiveness definitely affected the handling qualities of the aircraft. Any attempt to fixate on the basket and make a fine correction results in over control. I just have to accept getting it in the basket - that's about it.

e) Are you having to compensate? Compensation techniques were to increase my closure on the drogue and to focus exclusively on the S-3. (I) grip the stick lightly and only make small movements.

III. Feel System

a) Forces: too high / too low? Stick forces were light. (I) try to use very small inputs - just a light touch on the stick.

b) Stick deflection: too much / too little? Stick deflection was OK.

IV. PIO Tendency Rating
The oscillation - it's not divergent. Attempt to exert tight control causes oscillations. It's not divergent, but I'd say it's a PIO rating of 4.

V. Turbulence Rating
He was bouncing up and down a little bit. I'm going to say charlie.

VI. Drogue Stable?
Drogue was stable.

VII. Want to change your C-H rating?
No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R1	1	18	B	3	4	5	4	B

I. Pilot Rating (Cooper-Harper Scale)
- 5

II. Pitch Control During Approach to Basket

a) Undesirable motions?
- definite pitch bobble tendencies on this one
- bobbles turn into PIOs as gain increased
- not too bad when gain is low
- this one (is very bad)

b) Predictability?
- no comment

c) Initial response: too quick / too slow?
- feels OK to me

d) Does aggressiveness affect handling qualities?
- definitely, starts out OK and becomes PIO prone as gain increases

e) Are you having to compensate?
- yes, have to treat it gingerly to get it in

III. Feel System

a) Forces: too high / too low?
- seem OK

b) Stick deflection: too much / too little?
- fine

IV. PIO Tendency Rating
- 4

V. Turbulence Rating
- B

VI. Basket Stable?
- yes

VII. Want to change your C-H rating?
- no

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R1	5	32	B	3	3	5	4	A

I. Pilot Rating (Cooper-Harper Scale)
- 4

II. Pitch Control During Approach to Basket

a) Undesirable motions?
- aircraft appears to accelerate in pitch rate with a constant input
- a heaving sensation with any input; don't like it

b) Predictability?
- not really predictable in terms of magnitude of aircraft response

c) Initial response: too quick / too slow?
- starts off OK but seems to accelerate

d) Does aggressiveness affect handling qualities?
- tendency to PIO at high gain
- has big effect on handling qualities

e) Are you having to compensate?
- can't allow an input to stay in very long
- requires small sampling inputs
- cannot look at the basket without a PIO; must look at the tanker aircraft and use peripheral vision
- loosest stick grip of the day

III. Feel System

a) Forces: too high / too low?
- no comments

b) Stick deflection: too much / too little?
- no comments

IV. PIO Tendency Rating
- 4

V. Turbulence Rating
- A

VI. Basket Stable?
- yes

VII. Want to change your C-H rating?
- yes, the PIO rating drives a CH of 5

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R1	7	04	B	3	6	7	4	B

I. Pilot Rating (Cooper-Harper Scale)
- 7

II. Pitch Control During Approach to Basket
a) Undesirable motions?
- very PIO prone
b) Predictability?
- not predictable at all
c) Initial response: too quick / too slow?
- a heaving sensation
- pitch rate appears to accelerate
- feels like response ramps up
- too responsive
- I don't like it
d) Does aggressiveness affect handling qualities?
- workload goes down after hook-up
- PIOs build with gain
e) Are you having to compensate?
- yes, by relaxing grip on the stick
- must pinch the stick instead of grasping it
- have to fly almost open loop

III. Feel System
a) Forces: too high / too low?
- no comment
b) Stick deflection: too much / too little?
- no comment

IV. PIO Tendency Rating
- 4

V. Turbulence Rating
- B

VI. Basket Stable?
- pretty much, some oscillations due to tanker pilot inputs

VII. Want to change your C-H rating?
- no

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R2	4	19	A	3	6	1	1	C

I. Pilot Rating (Cooper-Harper Scale)
This is a nice airplane. Plane was controllable. Adequate performance was achieved. It was satisfactory without improvement. I'd say the airplane was excellent to good. There was really nothing I didn't like about it. I'd go ahead and give it an excellent. Pilot compensation not a factor. Pilot rating of one.

II. Pitch Control During Approach to Basket

a) Undesirable motions? There were no, I didn't feel any undesirable motions.
b) Predictability? It was very predictable and stable.
c) Initial response: too quick / too slow? The initial response felt about right.
d) Does aggressiveness affect handling qualities? (No comments).
e) Are you having to compensate? I don't think I was having to use any special compensating techniques.

III. Feel System

a) Forces: too high / too low? Stick forces felt right.
b) Stick deflection: too much / too little? Stick deflection was good

IV. PIO Tendency Rating
There was no undesirable motions that tended to occur. PIO rating of one.

V. Turbulence Rating
The biggest thing was increase in pilot effort because of turbulence. There was definitely more effort required. Deterioration of task performance was turbulence. I'm going to go with a Charlie.

VI. Drogue Stable?
You could see his aircraft getting bounced around with the turbulence and the basket was coming up and down a foot or two.

VII. Want to change your C-H rating? No

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R2	3	19	B	3	3	1	1	A

I. Pilot Rating (Cooper-Harper Scale)
- 1

II. Pitch Control During Approach to Basket

a) Undesirable motions?
- none

b) Predictability?
- very stable
- able to hit the eyeball precisely
- a good system

c) Initial response: too quick / too slow?
- not as sensitive (as 40)
- feels good

d) Does aggressiveness affect handling qualities?
- doesn't appear to

e) Are you having to compensate?
- not at all

III. Feel System

a) Forces: too high / too low?
- a tad on the high side

b) Stick deflection: too much / too little?
- no comments

IV. PIO Tendency Rating
- 1

V. Turbulence Rating
- A

VI. Basket Stable?
- yes

VII. Want to change your C-H rating?
- no

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R3	2	20	A	3	3	2	1	A

I. Pilot Rating (Cooper-Harper Scale)
It's controllable. Adequate performance isn't a problem. I'd say it was satisfactory without improvement. I'd say the airplane was between an excellent and good. I can't rule out some of the bobbling that was going on. I'd go with a good and a Cooper-Harper rating of two.

II. Pitch Control During Approach to Basket
a) Undesirable motions? There was a couple of times where I was hunting around farther back. There was some tendency for unwanted motions further out and I think it was more not being stable. On the last approach I fixated on the basket somewhat.
b) Predictability? I'd say the airplane is very predictable.
c) Initial response: too quick / too slow? The initial response felt about right.
d) Does aggressiveness affect handling qualities? (no comments)
e) Are you having to compensate? I stopped looking at the basket and looked at the airplane and just did what it took to get stable with his airplane and it all tamed out.

III. Feel System
a) Forces: too high / too low? (No comments).
b) Stick deflection: too much / too little? (No comments).

IV. PIO Tendency Rating
I don't think undesirable motions really occurred on this thing. I'd go with a PIO rating of one.

V. Turbulence Rating
Turbulence wasn't a factor. Turbulence was alpha.

VI. Drogue Stable?
Drogue was stable. We just came out of that turn on the second one and I don't think we were totally stable at the start.

VII. Want to change your C-H rating? No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R3	6	06	A	3	4	2	1	B

I. Pilot Rating (Cooper-Harper Scale)
Aircraft was controllable. Performance wasn't a problem. It was satisfactory without improvement. It's between an excellent and a good. I would say it was an excellent airplane. Pilot compensation was not really a factor to get the desired performance. I tell you what, I did have to - the stick forces were lighter than I want. I had to concentrate - grip the stick lighter. I'd go with a Cooper-Harper rating of 2. It's a good to an excellent airplane.

II. Pitch Control During Approach to Basket

a) Undesirable motions? No undesirable motions

b) Predictability? Predictability was good.

c) Initial response: too quick / too slow? Initial response was about right.

d) Does aggressiveness affect handling qualities? Aggressiveness I don't think would effect the handling qualities too much.

e) Are you having to compensate? Stick forces were somewhat light so I gripped the stick somewhat light so that I didn't over control.

III. Feel System

a) Forces: too high / too low? Feel system maybe a little too light.

b) Stick deflection: too much / too little? Stick deflection wasn't a factor.

IV. PIO Tendency Rating
I didn't see any undesirable motions. It's a one.

V. Turbulence Rating
Turbulence rating we'll go with a bravo as well.

VI. Drogue Stable?
The basket was for the most part stable. It bounced up and down a little bit, but not bad.

VII. Want to change your C-H rating? No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R3	1	20	B	3	3	3	2	B

I. Pilot Rating (Cooper-Harper Scale)
- 3
- airplane appears to be very solid

II. Pitch Control During Approach to Basket

a) Undesirable motions?
- a little bit of pitch bobble at the end game when my gain is highest

b) Predictability?
- no comments, good or bad

c) Initial response: too quick / too slow?
- a little too quick, but OK

d) Does aggressiveness affect handling qualities?
- a little; minor pitch bobbles occur at high gain

e) Are you having to compensate?
- yes, must be smooth and gentle
- can't grip the stick solidly, must pinch it instead
- definite feeling that I have to watch my own gain closer at the end game due to the feeling that if I put in more than a real small smooth input the jet may get away from me (i.e. at real high gain, the pitch bobbles may exceed the radius of the basket and could result in a missed engagement)

III. Feel System

a) Forces: too high / too low?
- fine

b) Stick deflection: too much / too little?
- fine

IV. PIO Tendency Rating
- 2

V. Turbulence Rating
- B

VI. Basket Stable?
- yes

VII. Want to change your C-H rating?
- no

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R4	4	35	A	3	3	2	1	B

I. Pilot Rating (Cooper-Harper Scale)
It's controllable. Performance was fine. I think it was satisfactory without improvement. I don't think it was excellent. I'm going to go with a good. Compensation wasn't really a factor. A Cooper-Harper rating of two.

II. Pitch Control During Approach to Basket

a) Undesirable motions? I wouldn't say there was undesirable motions. I wasn't doing as good a job with this one as I did with the last one (A3) at controlling the flight path as I approached the drogue.

b) Predictability? The airplane was predictable.

c) Initial response: too quick / too slow? Initial response felt about right.

d) Does aggressiveness affect handling qualities? I could get into a (situation) where I'd need to make flight path corrections three ft out and restabilize the airplane and continue with the approach.

e) Are you having to compensate? I felt I was having to deal with the flight path changes that were coming. I was not aware of the compensation techniques I was using, other than it was easy to restabilize at the end.

III. Feel System

a) Forces: too high / too low? Forces felt about right.

b) Stick deflection: too much / too little? Stick deflection was fine.

IV. PIO Tendency Rating
I didn't see a tendency for any undesirable motions. That's a one.

V. Turbulence Rating
I'll stick with a bravo.

VI. Drogue Stable?
Drogue was stable.

VII. Want to change your C-H rating? No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R4	6	21	A	3	3	2	1	B

I. Pilot Rating (Cooper-Harper Scale)
Controllability is not an issue. Adequate performance is possible. I'd say it was satisfactory without improvement. The compensation was not really a factor. I'd say the airplane was good. I didn't think it was excellent. I don't think I had to compensate a whole lot. I'll go with a Cooper-Harper rating of two.

II. Pitch Control During Approach to Basket

a) Undesirable motions? I didn't see really any undesirable motions of the airplane.

b) Predictability? It was predictable.

c) Initial response: too quick / too slow? The initial response was fine.

d) Does aggressiveness affect handling qualities? I don't know if I could control the flight path or the whatever as tightly as I wanted, but it was perfectly acceptable. It's definitely not as good as the last one (C1). The differences are slim, perhaps not quite as good.

e) Are you having to compensate? I think a lot of the stick forces are light but there was really not any special compensation that I could recognize myself doing.

III. Feel System

a) Forces: too high / too low? Forces were about right.

b) Stick deflection: too much / too little? I didn't see a problem with.

IV. PIO Tendency Rating
I didn't see a tendency for PIO. I'll give that a one.

V. Turbulence Rating
Turbulence rating, we'll give that a bravo.

VI. Drogue Stable?
Drogue was relatively stable.

VII. Want to change your C-H rating? No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R4	8	07	A	3	3	2.5	1	B

I. Pilot Rating (Cooper-Harper Scale)
It's controllable. Performance is not an issue. It's satisfactory without improvement. I think there were better ones. I call it good. Compensation is not that big of a factor. It's probably between a - I hate to use fair - fair sounds to harsh to me. I'm going to go good - with negligible deficiencies. A Cooper-Harper rating of two.

II. Pitch Control During Approach to Basket

a) Undesirable motions? No undesirable motions.

b) Predictability? It was predictable. Not as predictable as some, but very predictable. It isn't predictable enough for me to be able to just lift it up and put it back in the center.

c) Initial response: too quick / too slow? Initial response felt about right. These ones where I get more response out of the airplane to my stick input, I end up having to look at the S-3 quite a bit more and keep the basket in my peripheral view.

d) Does aggressiveness affect handling qualities? I can make the hookup, but.

e) Are you having to compensate? I felt I had to have somewhat of a light grip on the stick to make fine corrections. I think I had a tendency to want to come at the drogue faster because I didn't feel like I could control (the flight path) as precise as I could with other ones. To me that's a tendency that happens. I want to come at it quicker because I don't know if I can precisely place it. I know I can be good with it but I can't be precise as I'd like to be. But it's certainly quite good.

III. Feel System

a) Forces: too high / too low? Forces felt about right. Forces were light.

b) Stick deflection: too much / too little? Stick deflection was OK. Stick deflection was fine.

IV. PIO Tendency Rating
I didn't feel a tendency towards PIO. I'm going to give that a one.

V. Turbulence Rating
He bounced up and down a little bit. I'm going to give that a bravo.

VI. Drogue Stable?
The drogue was stable.

VII. Want to change your C-H rating? (Yes, based on inflight comments and review of performance Cooper-Harper rating of 2.5)

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R4	3	35	B	3	4	5	4	A

I. Pilot Rating (Cooper-Harper Scale)
- 4

II. Pitch Control During Approach to Basket

a) Undesirable motions?
- bobbles at high gain but I am able to stop it
- not able to disengage precisely

b) Predictability?
- predictably bad (due to PIOs)

c) Initial response: too quick / too slow?
- looks to be a little sluggish

d) Does aggressiveness affect handling qualities?
- definitely
- bobbles turn into PIOs as gain goes up

e) Are you having to compensate?
- yes, must back off level of aggressiveness
- have to hold the stick lighter
- must come out of the loop noticeably to get what I want

III. Feel System

a) Forces: too high / too low?
- too high for desired response

b) Stick deflection: too much / too little?
- no comments

IV. PIO Tendency Rating
- 4

V. Turbulence Rating
- A

VI. Basket Stable?
- yes

VII. Want to change your C-H rating?
- yes, PIO rating drives a CH of 5

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R4	5	21	B	3	5	5	4	B

I. Pilot Rating (Cooper-Harper Scale)
- 5

II. Pitch Control During Approach to Basket

a) Undesirable motions?
- PIO tendency at high gain (may have been tired by this time, late in the day, 9th FCS)

b) Predictability?
- not a really predictable system

c) Initial response: too quick / too slow?
- initial response is too slow

d) Does aggressiveness affect handling qualities?
- handling qualities deteriorate as gain increases
- workload goes down post hook-up

e) Are you having to compensate?
- must come out of the loop to stop PIOs

III. Feel System

a) Forces: too high / too low?
- fine

b) Stick deflection: too much / too little?
- no comments

IV. PIO Tendency Rating
- 4

V. Turbulence Rating
- B

VI. Basket Stable?
- most of the time
- some oscillations due to minor turbulence between cloud layers

VII. Want to change your C-H rating?
- no

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R4	7	07	B	3	3	1	1	B

I. Pilot Rating (Cooper-Harper Scale)
- 1

II. Pitch Control During Approach to Basket

a) Undesirable motions?
- none

b) Predictability?
- a solid system
- it feels good

c) Initial response: too quick / too slow?
- good initial response

d) Does aggressiveness affect handling qualities?
- doesn't seem to

e) Are you having to compensate?
- no
- similar to #10 (R3X), but a little better and a little quicker

III. Feel System

a) Forces: too high / too low?
- fine

b) Stick deflection: too much / too little?
- didn't notice

IV. PIO Tendency Rating
- 1

V. Turbulence Rating
- B

VI. Basket Stable?
- reasonably so

VII. Want to change your C-H rating?
- no

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R1X	4	22	A	3	4	5	3	A

I. Pilot Rating (Cooper-Harper Scale)

I have some heartburn with the way the airplane flew. It was very sensitive. Pitch control had undesirable motions. Even at 15 ft I was having, you could feel the aircraft going up and down. My flight path was coming up and down relative to the tanker. The airplane was controllable. Adequate performance was attainable with a tolerable workload. I would say however it requires improvement. I would want the airplane to be improved. Moderately objectional deficiencies.

II. Pitch Control During Approach to Basket

a) Undesirable motions? Undesirable up and down motions, aircraft has tendency to bob up and down, even at 15 ft in precontact you can feel, notice some problems with the flight path, it wants to kind of go up and down. My flight path is coming up and down relative to the tanker.

b) Predictability? I was going up and down the same amount.

c) Initial response: too quick / too slow? Too quick, very sensitive.

d) Does aggressiveness affect handling qualities? Very definite unwanted motions when I was attempting to make fine corrections.

e) Are you having to compensate? I'm trying to be very light on the stick and concentrate mainly on the tanker.

III. Feel System

a) Forces: too high / too low? Forces to me felt light.

b) Stick deflection: too much / too little? Stick deflection was probably little, very little stick deflection.

IV. PIO Tendency Rating

There was undesirable motions that tended to occur. Pilot attempts tight control and causes oscillations, I would say yes. They were not divergent type motions at all though. I think the task was compromised. I had back out the one time. I'm going to go with a PIO rating of three.

V. Turbulence Rating

I don't think we're having any problems with turbulence. I'm going to say turbulence rating of alpha.

VI. Drogue Stable?

I'm not sure the drogue is as stable as it was yesterday, but I don't feel any turbulence on the aircraft either.

VII. Want to change your C-H rating? No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R1X	3	22	B	3	3	4	3	A

I. Pilot Rating (Cooper-Harper Scale)
- 4

II. Pitch Control During Approach to Basket

a) Undesirable motions?
- bobbles a little
- definite PIO tendency
- don't have the fine pointing ability I had with other FCSs

b) Predictability?
- not really, due to the PIOs

c) Initial response: too quick / too slow?
- a little on the quick side

d) Does aggressiveness affect handling qualities?
- yes, bobbles increase as gain goes up
- as gain goes up PIOs increase

e) Are you having to compensate?
- yes, must back out of the loop as distance to the basket decreases
- I have to ease off my grip on the stick to avoid PIOs
- must accept the basket as opposed to the eyeball
- not my favorite

III. Feel System

a) Forces: too high / too low?
- seem OK

b) Stick deflection: too much / too little?
- a little too sensitive

IV. PIO Tendency Rating
- 4

V. Turbulence Rating
- A

VI. Basket Stable?
- yes

VII. Want to change your C-H rating?
- no

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R2X	2	37	A	4	4	1	1	A

I. Pilot Rating (Cooper-Harper Scale)
It was controllable. Adequate performance was not a problem. I'd say it was satisfactory without improvement. I like the way it flew. I'm between an excellent and a good here. Compensation wasn't really a factor for desired performance. I'd go with a rating of one. I like the way it flew.

II. Pitch Control During Approach to Basket

a) Undesirable motions? There were no undesirable motions. I don't know why, I get close to 15 ft and I have a tendency to start moving up and down a little bit. If there was any bobbling that happened as I got close to the basket, I think it was just cause I tried to look at the basket and tried to hit it in the center - just because I felt stable with the airplane.

b) Predictability? It was predictable.

c) Initial response: too quick / too slow? I didn't see the initial response as being to abrupt or to slow.

d) Does aggressiveness affect handling qualities? (no comments)

e) Are you having to compensate? I may have been grabbing the stick tighter than usual.

III. Feel System

a) Forces: too high / too low? Stick forces felt OK to me.

b) Stick deflection: too much / too little? Stick deflection was fine.

IV. PIO Tendency Rating
I didn't see there was an undesirable motion tending to occur at all. If it felt like anything to you in the end game, I think it was just - I started to stare at the basket more than anything else. I'm going to go with a one for that.

V. Turbulence Rating
Turbulence wasn't a factor. Turbulence was alpha.

VI. Drogue Stable?
Drogue was stable.

VII. Want to change your C-H rating? No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R2X	3	37	B	4	4	2	1	B

I. Pilot Rating (Cooper-Harper Scale)
- 2

II. Pitch Control During Approach to Basket

a) Undesirable motions?
- a little bit of pitch bobble at high gain (barely perceptible)

b) Predictability?
- I put the nose somewhere and it stays there
- able to chase a moving basket
- can precisely put the nose where I want it

c) Initial response: too quick / too slow?
- feels like a reasonably solid airplane

d) Does aggressiveness affect handling qualities?
- in a very minor way at high gain

e) Are you having to compensate?
- no, can aim for the eyeball instead of just the basket

III. Feel System

a) Forces: too high / too low?
- a little on the heavy side

b) Stick deflection: too much / too little?
- no comments

IV. PIO Tendency Rating
- 1

V. Turbulence Rating
- B

VI. Basket Stable?
- pretty much, it bounced around a little

VII. Want to change your C-H rating?
- no

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R3X	2	24	A	3	3	1	1	A

I. Pilot Rating (Cooper-Harper Scale)
Airplane was controllable. Adequate performance didn't require a whole lot of workload. I really liked the airplane. It was solid. It was predictable. I would way that it was satisfactory without improvement. It's between an excellent and a good. In fact, I think I would say it was excellent. It was very predictable and easy to fly. I'd give it a Cooper-Harper rating of one.

II. Pitch Control During Approach to Basket

a) Undesirable motions? I didn't see any undesirable motions.

b) Predictability? The airplane was very predictable.

c) Initial response: too quick / too slow? Initial response was about right.

d) Does aggressiveness affect handling qualities? I didn't have to get very aggressive with it. I don't know that would have made that big of a difference.

e) Are you having to compensate? I didn't feel like I was having to do anything special in the way of compensation.

III. Feel System

a) Forces: too high / too low? Stick forces are light. Stick forces were about right.

b) Stick deflection: too much / too little? Stick deflection was about right.

IV. PIO Tendency Rating
There were no undesirable motions. PIO rating of one.

V. Turbulence Rating
Turbulence wasn't a factor. Turbulence rating alpha.

VI. Drogue Stable?
Drogue was stable.

VII. Want to change your C-H rating? No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R3X	6	38	A	3	3	2	1	B

I. Pilot Rating (Cooper-Harper Scale)
Controllability is not a problem. Adequate performance isn't a problem. I'd say it was satisfactory without improvement. I wouldn't go so far as to say it was excellent. Not very much pilot compensation was required. I'd say that the airplane was good. Cooper-Harper of two. I couldn't control the flight path maybe as precisely as I wanted to but it was certainly good. You can definitely make contact with the basket.

II. Pitch Control During Approach to Basket

a) Undesirable motions ? No undesirable motions.

b) Predictability? The predictability was good.

c) Initial response: too quick / too slow? Initial response was about correct.

d) Does aggressiveness effect handling qualities? As I tried to do the fine stuff near the basket, I found that I could not control the flight path relative to the basket extremely precise.

e) Are you having to compensate? There was no special technique.

III. Feel System

a) Forces: too high / too low? Forces were about right.

b) Stick deflection: too much / too little? Stick deflection was fine.

IV. PIO Tendency Rating
There was no tendency for that. That's a one.

V. Turbulence Rating
The turbulence rating scale is still bravo.

VI. Drogue Stable?
The drogue was relatively stable.

VII. Want to change your C-H rating? No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R3X	8	10	A	3	3	2	1	C

I. Pilot Rating (Cooper-Harper Scale)
It's controllable. Performance was good. Satisfactory without improvement. I'd say it was between an excellent and a good in the way it felt to me. I don't feel I could stare at the basket and precisely point, but I could come close. I'm going to go with a - it's between a good and an excellent - almost a toss up. Pilot compensation wasn't really a factor. I'm going to call it excellent and give it a Cooper-Harper rating of one. The thing I liked about it was it was predictable. Again, I don't think it was as predictable as the one before (A4), but it was certainly fine for this task.

II. Pitch Control During Approach to Basket

a) Undesirable motions? There were no undesirable motions.

b) Predictability? The response was predictable. I didn't feel it was quite as predictable as the previous one (A4), but I could get it in there very well.

c) Initial response: too quick / too slow? The initial response was good.

d) Does aggressiveness affect handling qualities? I tried to slow down as I got in the basket. If I really had to get aggressive, I don't know if I could be extremely precise. But I could get aggressive with it.

e) Are you having to compensate? I didn't feel any special compensation techniques.

III. Feel System

a) Forces: too high / too low? Stick forces felt about right.

b) Stick deflection: too much / too little? Stick deflection felt about right.

IV. PIO Tendency Rating
The PIO rating was a one. I didn't sense any tendency for that.

V. Turbulence Rating
I don't think he was as stable as he could have been. I'm going to go with a Charlie for the turbulence rating scale.

VI. Drogue Stable?
The drogue was bouncing up and down a little bit when bounced up and down.

VII. Want to change your C-H rating?
(Yes, during the post flight debriefing I felt both my inflight comments and performance really indicated a Cooper-Harper rating of two - a good aircraft).

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R3X	1	24	B	3	3	1	1	B

I. Pilot Rating (Cooper-Harper Scale)
- 1

II. Pitch Control During Approach to Basket

a) Undesirable motions?
- none at all

b) Predictability?
- very predictable
- able to look at the probe tip and put it where I want it
- the best I've seen today

c) Initial response: too quick / too slow?
- feels more solid than experiment 20 (R3)
- doesn't feel like it'll get away

d) Does aggressiveness affect handling qualities?
- no
- able to be more aggressive
- don't have to consciously reduce gain

e) Are you having to compensate?
- no, don't have to pay alot of attention to the task

III. Feel System

a) Forces: too high / too low?
- good

b) Stick deflection: too much / too little?
- no comments

IV. PIO Tendency Rating
- 1

V. Turbulence Rating
- B

VI. Basket Stable?
- yes

VII. Want to change your C-H rating?
- no

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R3X	5	38	B	3	4	5	1	A

I. Pilot Rating (Cooper-Harper Scale)
- 5 (but I was tired by now and was evaluating a different task, eyeball vs basket)

II. Pitch Control During Approach to Basket

a) Undesirable motions?
- more trouble to stop the pitching motion than get it moving

b) Predictability?
- not able to put the nose where I want it

c) Initial response: too quick / too slow?
- OK

d) Does aggressiveness affect handling qualities?
- yes, performance goes down as gain goes up

e) Are you having to compensate?
- yes, must aim for the basket vice the eyeball
- can't hold the stick the way I want, must be looser
- workload goes down post hook-up

III. Feel System

a) Forces: too high / too low?
- no comment

b) Stick deflection: too much / too little?
- no comment

IV. PIO Tendency Rating
- 1

V. Turbulence Rating
- A

VI. Basket Stable?
- yes

VII. Want to change your C-H rating?
- no

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R3X	7	10	B	3	3	2	1	C

I. Pilot Rating (Cooper-Harper Scale)
- 2

II. Pitch Control During Approach to Basket

a) Undesirable motions?
- a comfortable system

b) Predictability?
- can follow a moving basket

c) Initial response: too quick / too slow?
- feels nice and solid
- not quite as quick as #2 (C1), but appears good

d) Does aggressiveness affect handling qualities?
- not really
- zero workload post hook-up

e) Are you having to compensate?
- lower workload than most other FCS tested
- I like this one
- one of the best I've felt

III. Feel System

a) Forces: too high / too low?
- fine

b) Stick deflection: too much / too little?
- no comment

IV. PIO Tendency Rating
- 1

V. Turbulence Rating
- C

VI. Basket Stable?
- most of the time, with some tanker pilot turns and rudder doublets

VII. Want to change your C-H rating?
- no

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R4X	4	11	A	3	3	2	1	B

I. Pilot Rating (Cooper-Harper Scale)
It's controllable. Adequate performance was achieved. It's satisfactory without improvement. It's between an excellent and a good as far it flies. I'd say it was excellent, a highly desirable airplane. Stick forces were lighter than I would have liked. Compensation wasn't really a factor to get the desired performance. I'm going to go with a Cooper-Harper of two.

II. Pitch Control During Approach to Basket

a) Undesirable motions? No undesirable motions.

b) Predictability? The airplane was predictable.

c) Initial response: too quick / too slow? The initial response was about right.

d) Does aggressiveness affect handling qualities? I never had to get aggressive with the airplane. I don't think that would have mattered a whole lot.

e) Are you having to compensate? The stick forces were light. I may have gripped the stick a little bit lighter than usual, but that was fine. One thing I noticed, the airplane it was fine. I don't think I could control the flight path as well as I would have liked to. I could get in there close and close was good enough for hitting the basket. I think to hit the center of the basket requires a lot, some workload.

III. Feel System

a) Forces: too high / too low? Stick forces were maybe a little lighter than I would have liked, but they were fine.

b) Stick deflection: too much / too little? No comments.

IV. PIO Tendency Rating
I never felt a tendency for PIO at all. No undesirable motions occurred. PIO rating is one.

V. Turbulence Rating
I'll go with bravo.

VI. Drogue Stable?
Drogue was stable.

VII. Want to change your C-H rating?
No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
R4X	5	39	B	3	3	3	2	A

I. Pilot Rating (Cooper-Harper Scale)
- 3

II. Pitch Control During Approach to Basket

a) Undesirable motions?
- little tendency to overshoot, by inches, inside the basket

b) Predictability?
- nose stops when input is taken out
- nose pointing is not as precise as some FCS but overshoots are measured in inches

c) Initial response: too quick / too slow?
- quick initial response, then deadbeat
- a little on the responsive side
- a little on the quick side

d) Does aggressiveness affect handling qualities?
- able to go right for the eyeball

e) Are you having to compensate?
- workload is nil once in the basket
- if willing to accept just the basket, its fine

III. Feel System

a) Forces: too high / too low?
- don't seem too high or too low

b) Stick deflection: too much / too little?
- no comment

IV. PIO Tendency Rating
- 2

V. Turbulence Rating
- A

VI. Basket Stable?
- yes

VII. Want to change your C-H rating?
- no

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
A1	4	40	A	3	3	6	2	A

I. Pilot Rating (Cooper-Harper Scale)
It was controllable. Adequate performance was achievable with a tolerable workload. It's not satisfactory without improvement. I'd say there's moderately objectionable deficiencies, probably very objectionable with the bucking motion. The problem with the trim is probably making it worse than it probably would have been. I'm going to go with a Cooper-Harper rating of six. Rating heavily influenced by jerkiness, rather than task performance (post flight debrief comment). Maybe a severe rating but was level 2 aircraft (post flight debrief comment)

II. Pitch Control During Approach to Basket

a) Undesirable motions? When I had light stick forces, I can feel this pulsing or bucking motion which I would call undesirable.

b) Predictability? It was predictable, but there was unwanted motions.

c) Initial response: too quick / too slow? The initial response was too quick.

d) Does aggressiveness affect handling qualities? Aggressiveness affected the handling qualities. The unwanted bobbing was aggravated the more aggressively I tried to track.

e) Are you having to compensate? Tried to keep a light stick grip.

III. Feel System

a) Forces: too high / too low? Had a problem keeping the stick forces light. They were anywhere from forward to aft stick forces.

b) Stick deflection: too much / too little? Stick deflection was OK.

IV. PIO Tendency Rating
When I attempted to exert tight control there were oscillations. There was a bucking motion, a feeling of a high frequency bucking motion, which is an undesirable motion. I never felt like I was into a PIO kind of a thing. The performance of the task wasn't compromised. I think trim was a player in there. PIO tendency rating two.

V. Turbulence Rating
Turbulence rating alpha.

VI. Drogue Stable?
Drogue was stable.

VII. Want to change your C-H rating?
No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
A1	6	12	A	3	3	6	3	B

I. Pilot Rating (Cooper-Harper Scale)
It was controllable. Adequate performance was attainable with a tolerable workload. However, there were deficiencies that warranted improvement. I'd say the deficiencies were more on the order of very objectionable versus moderately. Even though you could get desired performance, there was extensive compensation required. I'd give it a Cooper-Harper rating of six.

II. Pitch Control During Approach to Basket

a) Undesirable motions? There was undesirable motions for very small movements of the stick. You could feel the aircraft want to try to heave up and down. Very light stick to get that motion going. A heaving motion when you try to tighten up.

b) Predictability? Again, the acceleration, normal acceleration wasn't all that predictable. Not as precise as you'd like it to be. Very definitely unwanted motions when you really tighten up.

c) Initial response: too quick / too slow? Initial response was too quick. Very little stick forces would get the airplane into a heaving motion.

d) Does aggressiveness affect handling qualities? Aggressiveness affects handling qualities. As you try to tighten up that motion becomes worse.

e) Are you having to compensate ? Compensation was a light stick forces and tame inputs.

III. Feel System

a) Forces: too high / too low? The forces were slightly light.

b) Stick deflection: too much / too little? Were maybe smaller than you'd like.

IV. PIO Tendency Rating
There was definitely unwanted motions as you tightened up. Undesirable motions occur. I'd say the task was compromised and the PIO rating is a three.

V. Turbulence Rating
Turbulence rating is bravo.

VI. Drogue Stable?
(Drogue was stable).

VII. Want to change your C-H rating?
No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
A1	8	26	A	3	3	7-6	3	A

I. Pilot Rating (Cooper-Harper Scale)

Projected rating: It's controllable. Adequate performance is attainable with a tolerable workload. It does have deficiencies that warrant improvement. The adequate performance requires - it's between considerable and extensive compensation. I'd say for the task they were probably very objectionable deficiencies and adequate performance requires extensive compensation. I'd give it a Cooper-Harper rating of six.

Rating with the trim problem: There are some problems with the trim as well. They were not very big. I did have to trim and I did have some problems trimming it hands off. But it wasn't that bad. If I have to take into account (the trim problem) I'd give it a six either way - with or without this trim. The trim problem wasn't so bad with this one that I couldn't keep it in trim. Let me look at the scale one more time. Adequate performance attainable with a tolerable workload. I think with the trim problem, you have to go more with a requires improvement rather than just warrants it. I don't think this one wasn't so bad that I think controllability was an issue. I think I didn't like it. I'll give it a rating of seven. Major deficiencies - maximum tolerable workload - but controllability for this one is not an issue. I can keep up with the trim on this one.

II. Pitch Control During Approach to Basket

a) Undesirable motions? You could feel accelerations. I don't know if it was pitch or heave, but there was very definitely an acceleration for a very small movement of the stick.

b) Predictability? The initial response was not as predictable as I would like. Airplane initial response is somewhat unpredictable - tendency to bobble.

c) Initial response: too quick / too slow? Primary reason that I didn't like the airplane was - the initial response. I couldn't make a fine correction in close to the basket. I kind of got a response that was more than I wanted to for a small input of the stick. By the time the aircraft moved to my initial response, it had moved more than I would have wanted it to. Initial impression on this one - the stick is sensitive.

d) Does aggressiveness affect handling qualities ? Aggressiveness would affect the handling qualities. As I got in closer I was unable to precisely position the probe the way I would like to.

e) Are you having to compensate ? I'd have to grip the stick lightly and concentrate on making small inputs.

III. Feel System

a) Forces: too high / too low? The forces were a little bit light. Also, I'm having a little bit of problems trimming the airplane. It's not bad.

b) Stick deflection: too much / too little? I felt like I couldn't move the stick a whole lot or I'd get movements that I didn't want.

IV. PIO Tendency Rating

I could definitely sense to my initial inputs that as I tightened up the control, I could get into oscillatory motions. I never sensed they were divergent. Undesirable motions tend to occur. Task performance was - I think was somewhat compromised. I could easily see missing this basket. I'm going to go ahead with a PIO rating of three.

V. Turbulence Rating Turbulence rating was alpha. That wasn't a problem.

VI. Drogue Stable? Drogue was stable.

VII. Want to change your C-H rating? No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
A1	3	40	B	3	3	5	4	A

I. Pilot Rating (Cooper-Harper Scale)
- 4

II. Pitch Control During Approach to Basket
a) Undesirable motions?
- tendancy to bobble at low gain
- definite pitch bobble tendancies
- very sensitive stick
b) Predictability?
- no comments
c) Initial response: too quick / too slow?
- too quick
d) Does aggressiveness affect handling qualities?
- yes, perfromance deteriorates as gain goes up
e) Are you having to compensate?
- yes, must back out of the loop
- conscious effort to avoid PIOs

III. Feel System
a) Forces: too high / too low?
- seem fine
b) Stick deflection: too much / too little?
- no comment

IV. PIO Tendency Rating
- 4

V. Turbulence Rating
- A

VI. Basket Stable?
- yes

VII. Want to change your C-H rating?
- yes, the PIO rating drives it to a 5

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
A1	7	26	B	3	4	6-5	4	B

I. Pilot Rating (Cooper-Harper Scale)
- 6

II. Pitch Control During Approach to Basket

a) Undesirable motions?
- cycling trim
- changing my grip on the stick to make trim changes causes pitch bobbles
- it is a capable system but not comfortable
- PIO tendencies, response is just too quick

b) Predictability?
- workload doesn't go away post hook-up, but it does reduce a little

c) Initial response: too quick / too slow?
- more pitch sensitive than FCS #2 (C1)
- quick initial response

d) Does aggressiveness affect handling qualities?
- very sensitive stick; objectionable
- bobbles increase as gain goes up

e) Are you having to compensate?
- must loosen grip on the stick

III. Feel System

a) Forces: too high / too low?
- no comments

b) Stick deflection: too much / too little?
- no comments

IV. PIO Tendency Rating
- 4

V. Turbulence Rating
- B

VI. Basket Stable?
- reasonably so, but not as solid as the previous days

VII. Want to change your C-H rating?
- no, but if I try to divorce the trim problems, I think it may be a CH 5

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
A2	2	41	A	3	3	4	2	A

I. Pilot Rating (Cooper-Harper Scale)
It was controllable. Was adequate performance attainable with tolerable pilot workload - that's true. Is it satisfactory without improvement. I'd say there were deficiencies that warranted improvement. There was problems with trim. There was a tendency to get very sensitive, unwanted bobbles that happen. I'd go with minor but annoying deficiencies. Desired performance requires moderate compensation. As we got in close to the basket, I could sense a feeling of bobble and a need to tame my inputs quite a bit. I'll go with a Cooper-Harper rating of 4.

II. Pitch Control During Approach to Basket

a) Undesirable motions? For pitch control yes. As we got in closer, you could feel a little bobble.

b) Predictability? It was predictable, I didn't like the bobble.

c) Initial response: too quick / too slow? Initial response was quick, a little bit on the too quick side. The stick was very sensitive.

d) Does aggressiveness affect handling qualities? I think the more you try to tighten up, the more you're going to get in that bobble.

e) Are you having to compensate? The compensation that I was using was to tame my inputs.

III. Feel System

a) Forces: too high / too low? Stick forces were light. The stick was very sensitive. I had problems trimming the airplane. The trim problems would happen over a long period of time, 15 or 20 seconds. If I was holding aft stick, I would put in 3 bursts of forward trim spaced about 2 or 3 seconds apart. Stick forces would lighten up over the next several seconds and then I would end up having to push forward on the stick. I'm having a hard time with this configuration - trimming it.

b) Stick deflection: too much / too little? Stick deflection was fine.

IV. PIO Tendency Rating
Undesirable motions do occur. I could still accomplish the task, but there were undesirable motions. PIO rating of two.

V. Turbulence Rating
Turbulence wasn't a factor - that's alpha.

VI. Drogue Stable?
Drogue was stable.

VII. Want to change your C-H rating ?
No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
A2	6	27	A	3	4	5	2	B

I. Pilot Rating (Cooper-Harper Scale)
It's controllable. Adequate performance was attainable with a tolerable workload. First approach was flown too slowly. As far as was it satisfactory without improvement. I think there were deficiencies that warranted improvement in the aircraft. I'd say the deficiencies were moderately objectionable. There was considerable compensation in that I had to not get very rough with the airplane. I had to be light on the stick. The airplane was stable. It was easy to just drive in and track. I'll give it a Cooper-Harper rating of five.

II. Pitch Control During Approach to Basket
a) Undesirable motions? The airplane felt stable, but if you move the stick, there was somewhat of an abrupt feeling of acceleration with the airplane. Undesirable motions - I would say it was the abruptness if you tried to move the stick.
b) Predictability? The airplane was predictable, but I gripped the stick very lightly.
c) Initial response: too quick / too slow? Initial response was too quick, that kind of abruptness, jerkiness.
d) Does aggressiveness affect handling qualities? If I were to try to tighten up - the airplane was stable enough that I could lightly grip the stick and not have to make flight path changes. I think if you had to try to get aggressive with it though, you wouldn't like that abruptness.
e) Are you having to compensate? Compensation techniques were to grip the stick lightly.

III. Feel System
a) Forces: too high / too low? The stick forces if anything were slightly too low. There is a little bit of a problem keeping it trimmed.
b) Stick deflection: too much / too little? Stick deflection probably slightly too little.

IV. PIO Tendency Rating
There weren't any oscillations that occurred. Undesirable motions tend to occur. I would say - yes, but task performance is not compromised by it. PIO rating of two.

V. Turbulence Rating
The basket was bouncing a little bit, I'd give that a bravo.

VI. Drogue Stable?
Drogue wasn't as stable as I've seen it, but it wasn't that bad either.

VII. Want to change your C-H rating?
No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
A2	1	41	B	3	3	5	4	B

I. Pilot Rating (Cooper-Harper Scale)
- 4

II. Pitch Control During Approach to Basket

a) Undesirable motions?
- yes, the trim problems
- airplane acts like its in a continual short period all the time
- like riding a bucking bronco

b) Predictability?
- not, due to the trim; but otherwise very pointable

c) Initial response: too quick / too slow?
- a little too pitch sensitive

d) Does aggressiveness affect handling qualities?
- unable to tell

e) Are you having to compensate?
- yes, actively working the trim

III. Feel System

a) Forces: too high / too low?
- no comments, seemed OK

b) Stick deflection: too much / too little?
- no comments, seemed OK

IV. PIO Tendency Rating
- 4

V. Turbulence Rating
- B

VI. Basket Stable?
- yes

VII. Want to change your C-H rating?
- yes, the PIO rating drives a rating of 5

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
A2	5	27	B	3	3	5	4	A

I. Pilot Rating (Cooper-Harper Scale)
- 5

II. Pitch Control During Approach to Basket

a) Undesirable motions?
- tendency to pitch bobble at low gain
- tendency to pitch bobble as I play with the trim
- more bobbles as I sample the stick
- don't like this trim at all

b) Predictability?
- not very (due to the cycling trim)
- have to hunt and peck with the stick

c) Initial response: too quick / too slow?
- feels like #2 (C1), maybe a little more solid
- pretty sensitive in pitch

d) Does aggressiveness affect handling qualities?
- yes, performance goes down as gain goes up

e) Are you having to compensate?
- yes, must guard the stick closely to avoid bobbles

III. Feel System

a) Forces: too high / too low?
- continually cycle

b) Stick deflection: too much / too little?
- continually cycle

IV. PIO Tendency Rating
- 4

V. Turbulence Rating
- A

VI. Basket Stable?
- yes, but not as stable as the previous two flights

VII. Want to change your C-H rating?
- no

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
A3	4	28	A	3	3	2	1	B

I. Pilot Rating (Cooper-Harper Scale)
It was controllable. Adequate performance was achieved with a tolerable pilot workload. I'd say it was satisfactory without improvement. I like the airplane. It was between an excellent and a good. Pilot compensation really wasn't that big a factor. I could sense somewhat (a quickness) and again the trim was probably influencing the way the stick forces were changing. I'm going to go with a good. Give it a Cooper-Harper rating of two.

II. Pitch Control During Approach to Basket

a) Undesirable motions? I didn't see any undesirable motions. It was so stable that you could just fly it in.

b) Predictability? The airplane was very stable. It was easy to just line it up and drive it in. I felt like I could hit the center of the basket fairly easily.

c) Initial response: too quick / too slow? Initial response was about correct. I could sense a little bit of a quickness to it, but the airplane physically wasn't moving relative to the S-3.

d) Does aggressiveness affect handling qualities? I never had to get aggressive with it. The airplane was stable.

e) Are you having to compensate? I wasn't trying to use any special techniques for compensation that I was aware of.

III. Feel System

a) Forces: too high / too low? Same deal with having a problem keeping the aircraft trimmed for hands off. It was changing trim through out the task although I tried to keep it as close to correct as I could.

b) Stick deflection: too much / too little? Stick deflection was about right.

IV. PIO Tendency Rating
I didn't feel any undesirable motions. I'd give it a PIO rating of one.

V. Turbulence Rating
As far as the turbulence goes, I'll stick with a bravo.

VI. Drogue Stable?
Drogue was stable.

VII. Want to change your C-H rating?
No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
A3	6	14	A	3	3	1	1	B

I. Pilot Rating (Cooper-Harper Scale)
It's controllable. You can get performance. With the exception of the trim problem, it's satisfactory without improvement. It's between an excellent and a good. You can precisely nail the basket where you want to. I would say it was excellent. Pilot compensation is not a factor at all. It's one of the few kinds - I can even stare at the basket if I wanted to. I'm going to say a Cooper-Harper rating of one.

II. Pitch Control During Approach to Basket

a) Undesirable motions? There wasn't any undesirable motions.

b) Predictability? It was very predictable, very easy to point the airplane and make it (go) where you want to go, especially in the end game. The response was very predictable. What I like about this, there is very fine control. You can hit in the center if you want to. I can shift what I'm looking at from the tanker to the basket in the end game and try to precisely position it if I wanted to.

c) Initial response: too quick / too slow? The initial response was perhaps a little quick, but it wasn't that bad.

d) Does aggressiveness affect handling qualities? I didn't see that aggressiveness would affect the handling qualities. The airplane was kind of stable. I don't know how aggressive you could really get with it.

e) Are you having to compensate? There was no - the compensation was trying to keep the airplane trimmed throughout the task.

III. Feel System

a) Forces: too high / too low? Stick forces were high and cycling from aft to forward throughout the task. There's problems with getting the airplane trimmed.

b) Stick deflection: too much / too little? The stick deflection was about right.

IV. PIO Tendency Rating
There was no undesirable motions. That's a one.

V. Turbulence Rating
Turbulence rating is a rating of bravo.

VI. Drogue Stable?
Drogue was stable.

VII. Want to change your C-H rating?
No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
A3	8	42	A	3	4	7	1	B

I. Pilot Rating (Cooper-Harper Scale)

Projected rating: It was controllable. Adequate performance was attainable with a tolerable workload and I'd say satisfactory without improvement. The airplane was good. Pilot compensation wasn't really a factor to get desired performance. It's between an excellent a good and an excellent for the way you can perform the task. I'll go with a Cooper-Harper rating of two.

Rating the airplane with the trim problems: The trim was more of a factor for this one than it was for the previous one (A1). Again I felt the airplane was controllable. However, deficiencies require improvement. The trim problem would have to be improved. Again, I don't really feel that I would have to abandon the task and lose control of the aircraft. There are major deficiencies that require improvement. I would go again with a rating of seven.

II. Pitch Control During Approach to Basket

a) Undesirable motions? I didn't sense any in the aircraft.

b) Predictability? The airplane was very predictable in its initial response. The thing that I liked about the airplane was precision. You can make fine predictable corrections in the end.

c) Initial response: too quick / too slow? The initial response is very predictable. If I needed to lift the probe up to put it in the basket, I can do that. The initial response is very predictable for fine corrections in the end. The initial response is so predictable that I can afford to spend a lot of time starring at the basket and make a fine correction in close. A lot of other airplanes you have to stay stable with the S-3 and take glances at the basket or view the basket in your peripheral vision with occasional glances.

d) Does aggressiveness affect handling qualities? I think you could get aggressive with the aircraft and make a fine correction in close.

e) Are you having to compensate? I didn't feel any real special need to compensate other than to try to keep up with this trim.

III. Feel System

a) Forces: too high / too low? Stick forces were maybe a little heavier than usual because of the trim problem. But you could get it into trim and at that time the stick forces felt good to slightly light. The trim is worse on this one than the previous one (A1). I can't keep it in trim as long as I could with the other one. The ability to trim the airplane is very poor.

b) Stick deflection: too much / too little? Stick deflection was in my mind OK.

IV. PIO Tendency Rating

PIO rating is one.

V. Turbulence Rating

Turbulence rating - a bravo.

VI. Drogue Stable?

I thought the drogue was for the most part stable. Maybe not as stable as some of the drogues I've seen before. I'll give the turbulence rating a bravo.

VII. Want to change your C-H rating ? No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
A3	3	28	B	3	3	5	3	A

I. Pilot Rating (Cooper-Harper Scale)
- 5

II. Pitch Control During Approach to Basket
a) Undesirable motions?
- yes, the trim cycles continuously, although not as drastically as the other trim problems
b) Predictability?
- not very, due to the trim cycling
c) Initial response: too quick / too slow?
- appears sluggish
d) Does aggressiveness affect handling qualities?
- can't really tell, must always be aggressive to keep the trim in check
e) Are you having to compensate?
- yes, have to stop when the trim passes through neutral
- unacceptable workload

III. Feel System
a) Forces: too high / too low?
- stick forces and deflections get to be too high
b) Stick deflection: too much / too little?
- get to be too big as trim cycles

IV. PIO Tendency Rating
- 3

V. Turbulence Rating
- A

VI. Basket Stable?
- yes

VII. Want to change your C-H rating?
- no

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
A3	5	42	B	3	3	3	2	A

I. Pilot Rating (Cooper-Harper Scale)
- 3 (very biased due to the cycling trim; would be worse if I evaluated the entire FCS as opposed to this rating which attempts to isolate the trim problem out of the FCS)

II. Pitch Control During Approach to Basket

a) Undesirable motions?
- another cycling trim FCS
- not as bad as #43 (A4) in terms of rate or magnitude of trim cycles
- workload doesn't go away post hook-up due to the cycling trim

b) Predictability?
- think it would be a good system if trim were not a factor
- good pointing capability
- pretty nice when trimmed up

c) Initial response: too quick / too slow?
- sluggish

d) Does aggressiveness affect handling qualities?
- can't tell, always high gain

e) Are you having to compensate?
- yes, for the cycling trim

III. Feel System

a) Forces: too high / too low?
- maybe a little on the high side

b) Stick deflection: too much / too little?
- annoying as it cycles

IV. PIO Tendency Rating
- 2

V. Turbulence Rating
- A

VI. Basket Stable?
- yes

VII. Want to change your C-H rating?
- yes, but I can't due to the attempt to divorce the trim problems from the FCS
- the entire system as a whole would not be level 1

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
A3	7	14	B	3	3	5-3	2	A

I. Pilot Rating (Cooper-Harper Scale)
- 5

II. Pitch Control During Approach to Basket

a) Undesirable motions?
- workload due to trim is too high
- workload doesn't go away post hook-up

b) Predictability?
- gross acquisition during trim cycling (is really bad)
- reasonably solid when trim is neutral
- trim cycling makes it unpredictable

c) Initial response: too quick / too slow?
- feels more solid than #26 (A1)
- not as quick as #26 (A1)
- pretty good initial characteristics, I like it

d) Does aggressiveness affect handling qualities?
- can't tell, too busy fighting the trim

e) Are you having to compensate?
- primarily for the trim
- overall better than #26 (A1)

III. Feel System

a) Forces: too high / too low?
- no comments

b) Stick deflection: too much / too little?
- no comments

IV. PIO Tendency Rating
- 2

V. Turbulence Rating
- A

VI. Basket Stable?
- yes

VII. Want to change your C-H rating?
- no

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
A4	2	29	A	3	3	2	1	A

I. Pilot Rating (Cooper-Harper Scale)
Was it controllable - yes. Was adequate performance attainable - yes. Now as far as satisfactory without improvement goes - there were definitely deficiencies in the trim system that warrant improvement. As far as when the airplane was trimmed, it was fine. I don't know how to resolve that conflict exactly. When it was in trim, I'd go with - it was between an excellent and a good. It was very easy to accomplish the task. I'm going to go with a good and a Cooper-Harper rating of two. I didn't see that I was having to compensate a whole lot in what I was doing - other than to deal with stick forces that seemed to be cycling on their own.

II. Pitch Control During Approach to Basket

a) Undesirable motions? I didn't feel any undesirable motions.

b) Predictability ? I felt the airplane was real stable. The airplane was predictable.

c) Initial response: too quick / too slow? The initial response was fine.

d) Does aggressiveness affect handling qualities? (no comments)

e) Are you having to compensate? I didn't see that I was having to compensate a whole lot in what I was doing - other than to deal with stick forces that seemed to be cycling on their own.

III. Feel System

a) Forces: too high / too low? They were way to big forces for me. But I don't think it was a problem with the - when I had it trimmed and I had to make corrections, the forces felt fine to me. You can feel the trim kind of do a slow cycle. I think trim is going to be a big player in what we feel about these ones.

b) Stick deflection: too much / too little? Again, when it was trimmed and I was trying to accomplish the task, they felt fine. As the trim started to walk one way or the other, I was having to move the stick well forward or well aft just to try to maintain my present position.

IV. PIO Tendency Rating
There's no tendency to PIO what so ever. I'd go with a PIO rating of one.

V. Turbulence Rating
Turbulence wasn't a factor. Turbulence rating is alpha.

VI. Drogue Stable?
Drogue was stable.

VII. Want to change your C-H rating?
No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
A4	4	43	A	3	3	1	1	B

I. Pilot Rating (Cooper-Harper Scale)
It's controllable. Adequate performance is achievable. I'd say it was satisfactory without improvement. I'd go so far as to say it was excellent just because if I wanted to hit the center I could do that. It wasn't hard at all. Pilot compensation wasn't really a factor for desired performance. I'm going to give it a Cooper-Harper rating of one. You can do this (probe and drogue) even despite the fact that you have very undesirable stick forces that were changing throughout the task. It was still so stable that you could do it.

II. Pitch Control During Approach to Basket

a) Undesirable motions? I didn't see any undesirable motions.

b) Predictability? The airplane is very predictable. I liked how stable the airplane was. You can just line up with the basket and drive at it. I could even shift and look at the basket a lot more if I want to because the airplane isn't going to do anything, cause its stable.

c) Initial response: too quick / too slow? Because the airplane was stable, I didn't have to put in a whole lot of inputs. Any inputs I do, it happens slow and very predictably.

d) Does aggressiveness affect handling qualities? (no comments)

e) Are you having to compensate? (no comments)

III. Feel System

a) Forces: too high / too low? Some problems with the trim again. I probably have 10 lb aft stick right now (similar comments, more than once).

b) Stick deflection: too much / too little? (no comments)

IV. PIO Tendency Rating
PIO tendency, there was none. It's a rating of one.

V. Turbulence Rating
We'll call it bravo. Turbulence wasn't that big of a factor.

VI. Drogue Stable?
Drogue was stable.

VII. Want to change your C-H rating?
No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
A4	6	43	A	3	4	2	1	B

I. Pilot Rating (Cooper-Harper Scale)
The aircraft is controllable. It's no problem getting the performance I want. Is it satisfactory without improvement - I like the way I can put it in there. I don't like the way the trim is. We've been trying to take the trim issue out of there and get it as close to trim as we can and perform the task that way. I'd say the airplane is between a good and a excellent for accomplishing the task - when it's in trim. I can precisely put the thing in there. I'm going to go with a good. Cooper-Harper rating of two. What I like about the airplane is that you can precisely change your pitch or flight path. You can make fine corrections close to the basket. It's predictable that way. What I don't like is the way that the stick forces are changing. I can't get the airplane trimmed so that it can fly hands off.

II. Pitch Control During Approach to Basket

a) Undesirable motions? There are no undesirable motions that occur.

b) Predictability? The response is very predictable. The airplane is stable.

c) Initial response: too quick / too slow? I don't consider it too quick or too slow.

d) Does aggressiveness affect handling qualities ? I was off in position in the last one - was out of position on the last two. I could bring it up to the middle. I could put it into the basket without any problems. Other configurations, I'm not sure I could make that big of a change in the end game.

e) Are you having to compensate? I didn't feel any special technique as far as compensation. Other than having to deal with a lot of the stick forces that are alternating between aft and forward and back to aft again, which affect how well I can release or put the drogue back into the position as I back out.

III. Feel System

a) Forces: too high / too low?

b) Stick deflection: too much / too little?

IV. PIO Tendency Rating
There were no undesirable motions that occur. PIO rating is one.

V. Turbulence Rating
As far as turbulence goes. I'll stick with a bravo. It's a fairly stable drogue.

VI. Drogue Stable?
Drogue was fairly stable.

VII. Want to change your C-H rating?
No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
A4	8	29	A	3	4	8-1	1	B

I. Pilot Rating (Cooper-Harper Scale)

Projected rating: As far as the rating if I can eliminate the trim problem. It was controllable. It was good for performance. It was satisfactory without improvement. I think it was an excellent response to hit that basket routinely and stabilize there. I'd give it an excellent and a pilot rating of one.

Rating the airplane with the trim problem: As far as how I would rate the airplane with the trim problem. I think improvement is mandatory - that there's a potential to lose control of the airplane. I think I can make the task happen, but I can't say that I can stay on that drogue enough to get an off load. The stick forces if I'm not keeping up with them may get to the point where I have to abandon the task and get away from the other airplane to get the trim under control again. I feel that there's a high potential that you'd have to abandon the task - have to abandon the air refueling task though if you can't keep up with the trim forces. I would swing all the way to the other end and give a Cooper-Harper rating ten - that improvement is mandatory. As far as doing the hookup goes, I think you can do that. As far as taking an off load. There may be a time when you don't. We'll confine it to hooking it up. There is between considerable to intense compensation going on to do that. I'd say it's a considerable compensation - something that you can do but it's very hard - requires a lot of effort. I'll go with a Cooper-Harper rating of eight.

II. Pitch Control During Approach to Basket

a) Undesirable motions? There were none. There was very undesirable trim.

b) Predictability? The initial response is very predictable. You can be very precise. You can very precisely, up and down, point the airplane. You know it's very good even despite the bad stick forces that I have to deal with.

c) Initial response: too quick / too slow? The initial response was extremely predictable.

d) Does aggressiveness affect handling qualities? It is so stable that you don't have to get aggressive. You can put the airplane where you want. I feel like I can control the flight path almost directly.

e) Are you having to compensate? I didn't feel anything special that I needed to do, other than to deal with these very bad trim forces.

III. Feel System

a) Forces: too high / too low? The forces obviously cycled from being way to far aft to way to far forward. The problem is the trim. The trim is really bad.

b) Stick deflection: too much / too little? The stick deflection was right to me. When I was in trim.

IV. PIO Tendency Rating

PIO rating is a one. There's no tendency (towards PIO)

V. Turbulence Rating

Turbulence level will call bravo.

VI. Drogue Stable?

(no comments)

VII. Want to change your C-H rating? No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
A4	3	29	B	3	3	6	3	A

I. Pilot Rating (Cooper-Harper Scale)
- 6

II. Pitch Control During Approach to Basket

a) Undesirable motions?
- a squirrely trim system
- trimmability is a pain
- variable stick forces all the way in

b) Predictability?
- not really, due to the trim cycling
- can learn to compensate

c) Initial response: too quick / too slow?
- no comment

d) Does aggressiveness affect handling qualities?
- can't tell, always the same high level of pilot gain

e) Are you having to compensate?
- yes, cannot relax grip on the stick
- highest workload that I've seen yet (2, 18, 41, 20, 24, 37)

III. Feel System

a) Forces: too high / too low?
- get to be too high
- increase without trim

b) Stick deflection: too much / too little?
- gets to be too much
- got to the stops

IV. PIO Tendency Rating
- 3

V. Turbulence Rating
- A

VI. Basket Stable?
- yes

VII. Want to change your C-H rating?
- no (but did really start off thinking it was in the 7-9 category but was led into the 3-6 category by the observation pilot)

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
A4	5	43	B	3	4	5	3	A

I. Pilot Rating (Cooper-Harper Scale)
- 5

II. Pitch Control During Approach to Basket

a) Undesirable motions?
- another trim problem
- fastest cycling trim with higher forces and deflections
- I just don't like these

b) Predictability?
- not (due to terrible trim)

c) Initial response: too quick / too slow?
- sluggish
- takes a big input to get any nose movement

d) Does aggressiveness affect handling qualities?
- can't tell

e) Are you having to compensate?
- yes, high workload
- be glad to get rid of this one
- had high workload even after hooked-up
- the entire process is a handful

III. Feel System

a) Forces: too high / too low?
- too heavy

b) Stick deflection: too much / too little?
- continually cycling

IV. PIO Tendency Rating
- 3

V. Turbulence Rating
- A

VI. Basket Stable?
- yes

VII. Want to change your C-H rating?
- no

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
A4	5	15	B	3	3	9-3	1	A

I. Pilot Rating (Cooper-Harper Scale)
- 3 if I can somehow disregard the trim problems
- 9 if I consider the entire experience (got to full aft stick with the nose still going down)

II. Pitch Control During Approach to Basket

a) Undesirable motions?
- only the trim

b) Predictability?
- I like the way I can position the tip when I don't have to concentrate on the trim
- gross acquisition is easy to do

c) Initial response: too quick / too slow?
- sluggish

d) Does aggressiveness affect handling qualities?
- can't tell, too busy working the trim

e) Are you having to compensate?
- just for the trim

III. Feel System

a) Forces: too high / too low?
- cycle from too high to too low

b) Stick deflection: too much / too little?
- cycles to the extremes

IV. PIO Tendency Rating
- 1

V. Turbulence Rating
- A

VI. Basket Stable?
- yes

VII. Want to change your C-H rating?
- no, but see above comments

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
A4	7	29	B	3	4	7-5	3-2	A

I. Pilot Rating (Cooper-Harper Scale)
- 7 (but was pretty much talked into to it using the "it has to be fixed" mentality)

II. Pitch Control During Approach to Basket

a) Undesirable motions?
- faster cycling trim (than #14) (A3)

b) Predictability?
- not, due to the trim

c) Initial response: too quick / too slow?
- sluggish
- slower than 14 (A3) or 26 (A1)

d) Does aggressiveness affect handling qualities?
- too hard to tell

e) Are you having to compensate?
- yes. for the trim
- use power to drive it in when trimmed

III. Feel System

a) Forces: too high / too low?
- excessive, objectionable stick forces
- worst trim forces of 14 (A3), 26 (A1), and 29 (A4)

b) Stick deflection: too much / too little?
- gets to extremes

IV. PIO Tendency Rating
- 3 for the overall system
- 2 if I can somehow disregard the trim

V. Turbulence Rating
- A

VI. Basket Stable?
- yes

VII. Want to change your C-H rating?
- no

NOTE: Relatively speaking between experiments 14 (A3), 26 (A1), and 29 (A4)
- 14 (A3) is the best
- 26 (A1) and 29 (A4) are a tie for the worst
  - -- as tested with the bad trim, 26 (A1) is better than 29 (A4)
  - -- not including trim problems, 29 (A4) is better than 26 (A1)

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
C1	4	30	A	3	3	2	1	B

I. Pilot Rating (Cooper-Harper Scale)
The aircraft was controllable. Adequate performance was achieved. I think it was satisfactory without improvement. I wouldn't say is was excellent, I'd say it was good. Pilot compensation wasn't a factor, but it was a little bit - lighter on the stick forces than I would have liked. It's between a good and a fair more. I'm going to go with a Cooper-Harper rating of two. Compensation wasn't really a factor.

II. Pitch Control During Approach to Basket

a) Undesirable motions? There were no real undesirable motions.

b) Predictability? The airplane was predictable.

c) Initial response: too quick / too slow? The initial response was fine.

d) Does aggressiveness affect handling qualities? I never had to get aggressive with the airplane. It was predictable enough that I didn't have to do that.

e) Are you having to compensate? Compensation technique for the light stick forces - I gripped the stick a little bit lighter and tried to tame my inputs.

III. Feel System

a) Forces: too high / too low? Stick forces were a little bit light, I would have preferred to have them a little bit heavier.

b) Stick deflection: too much / too little? No comments.

IV. PIO Tendency Rating
No Divergent oscillations. Attempting tight control didn't cause any oscillations. I didn't see any undesirable motions. PIO rating is one.

V. Turbulence Rating
The aircraft felt a little bit more stable than before. I'm going to go with an increase in pilot effort, may be more effort, but not a significant deterioration (in task performance). Turbulence rating is bravo.

VI. Drogue Stable?
Drogue was stable.

VII. Want to change your C-H rating?
No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
C1	6	30	A	3	3	1	1	B

I. Pilot Rating (Cooper-Harper Scale)
Controllability is not an issue. performance is not an issue. It's satisfactory without improvement. I'd say it was excellent, a highly desirable airplane. I'd like higher stick forces. Compensation wasn't a factor. Pilot rating is one. If I could compare this one with the other one (A3), it's probably not right to do. This is a good airplane. I don't know if I can control - It's good, I'll let it go at that.

II. Pitch Control During Approach to Basket

a) Undesirable motions? No undesirable motions.

b) Predictability? It's predictable. Very predictable.

c) Initial response: too quick / too slow? The initial response was good.

d) Does aggressiveness affect handling qualities? We came in and stopped close to the basket and that didn't seem to affect the handling qualities.

e) Are you having to compensate? There was nothing special. Maybe I gripped the stick a little bit lighter than normal, but not bad.

III. Feel System

a) Forces: too high / too low? Maybe the stick forces were slightly light, lighter than I would want it to be. Light but not bad.

b) Stick deflection: too much / too little? The stick deflection was fine.

IV. PIO Tendency Rating
PIO rating is a one, that's not a factor.

V. Turbulence Rating
Turbulence rating, I'll call it a bravo.

VI. Drogue Stable?
Drogue was relatively stable.

VII. Want to change your C-H rating?
No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
C1	3	30	B	3	3	3	2	A

I. Pilot Rating (Cooper-Harper Scale)
- 3

II. Pitch Control During Approach to Basket
a) Undesirable motions?
- stick seems to be a little on the light side
- more sensitive in pitch (than 29)
- not as forgiving of large or abrupt inputs
- a pretty good nose pointing machine
b) Predictability?
- reasonably so
c) Initial response: too quick / too slow?
- I like the initial response
d) Does aggressiveness affect handling qualities?
- yes, more apparent that level of aggressiveness affects performance
- must watch my own level of aggressiveness
e) Are you having to compensate?
- yes, not grasping the stick very tight
- must concentrate more on smooth inputs
- have to be careful
- cannot look at the probe without bobbling

III. Feel System
a) Forces: too high / too low?
- a little on the light side
b) Stick deflection: too much / too little?
- no comments

IV. PIO Tendency Rating
- 2

V. Turbulence Rating
- B

VI. Basket Stable?
- yes

VII. Want to change your C-H rating?
- no

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
C1	5	30	B	3	3	2	1	A

I. Pilot Rating (Cooper-Harper Scale)
- 2

II. Pitch Control During Approach to Basket
a) Undesirable motions?
- feels normal
b) Predictability?
- can aim at the eyeball without a problem
- good fine pointing ability
c) Initial response: too quick / too slow?
- good, a stable, conventional sort of an airplane
d) Does aggressiveness affect handling qualities?
- no
e) Are you having to compensate?
- no
- workload disappears post hook-up

III. Feel System
a) Forces: too high / too low?
- fine
b) Stick deflection: too much / too little?
- didn't notice

IV. PIO Tendency Rating
- 1

V. Turbulence Rating
- A

VI. Basket Stable?
- yes

VII. Want to change your C-H rating?
- no

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
C1X	4	31	A	3	3	6	3	B

I. Pilot Rating (Cooper-Harper Scale)
It was controllable. Was adequate performance attainable - yes. Was it satisfactory without improvement - I'd say no. There were deficiencies that warranted improvement. I would say the deficiencies, even though desired performance could be achieved, the deficiencies required a lot of compensation on the pilot's part. It's between considerable and extensive compensation. I could feel a tendency, even on the drogue itself, that I could get into the oscillations. I would call the deficiencies moderately objectionable and that extensive compensation was required. You had to very purposely be gentle with the stick. Cooper-Harper rating of six.

II. Pitch Control During Approach to Basket

a) Undesirable motions? The aircraft had a very definite abruptness. You can feel it bobbling. I don't even notice flight path changes relative to the S-3, but the nose is bobbing up and down.

b) Predictability? With very light stick forces, the nose would pitch up and down. It would predictably do that.

c) Initial response: too quick / too slow? The initial response is way too quick.

d) Does aggressiveness affect handling qualities? I think if you tried to be aggressive with the airplane in close to the basket, you'd end up with some very - the undesirable motions would be amplified.

e) Are you having to compensate? The compensation technique is to purposely not try to move the stick hardly at all.

III. Feel System

a) Forces: too high / too low? It was very light stick forces. Any little movement of the stick would cause an abrupt response.

b) Stick deflection: too much / too little? It seemed like very little deflection of the stick would cause undesirable motions. It was a pitching acceleration type motion.

IV. PIO Tendency Rating
Definitely when you tried to exert tight control you got into oscillations. I wouldn't say they were divergent by any means. I don't see that we got into any sustained oscillations on this one (configuration). Undesirable motions did occur. I thought the task performance could be compromised by it. I'm going to go with a PIO rating of three.

V. Turbulence Rating
Turbulence was bravo.

VI. Drogue Stable?
Drogue was stable

VII. Want to change your C-H rating?
No.

PILOT COMMENT CARD

CONF	FLT #	EXP #	PILOT	Hookups	Attempts	HQR	PIOR	TURB
C1X	5	17	B	3	3	5	2	A

I. Pilot Rating (Cooper-Harper Scale)
- 4

II. Pitch Control During Approach to Basket

a) Undesirable motions?
- this one is very jumpy, don't like it
- get bobbles during trimming
- very abrupt, a bucking kind of a motion

b) Predictability?
- not very
- acts like 32 (R1) but with a quicker response
- workload doesn't go away post hook-up, but not as bad as #43 (A4)

c) Initial response: too quick / too slow?
- very quick
- any input causes an instant response
- over sensitive

d) Does aggressiveness affect handling qualities?

definitely, it has a big effect on performance

e) Are you having to compensate?
- can't hold the stick the way I want too
- have to pinch vice grip the stick
- must fly by guarding the stick
- gets easier if I go faster (higher closure)

III. Feel System

a) Forces: too high / too low?
- seem OK

b) Stick deflection: too much / too little?
- seems to be too little breakout

IV. PIO Tendency Rating
- 2 (although post flight video review looked worse than a 2)

V. Turbulence Rating
- A

VI. Basket Stable?
- yes

VII. Want to change your C-H rating?
- yes, to a 5 after inflight review of the comment card I talked myself into a 5

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Vita

Capt. Michael J. Taschner was born in St. Paul, Minnesota on 25 October 1959. He earned a Bachelor of Science Degree in Aerospace Engineering with High Distinction from the University of Minnesota in 1982. While attending the University of Minnesota, he participated in a summer intern program at the Johnson Space Center, and worked in the Crew Systems Division. In September 1982 he was commissioned a Second Lieutenant in the United States Air Force through Officer Training School. After graduating from Undergraduate Pilot Training in 1983, Capt. Taschner served as a T-38A Instructor Pilot and Flight Examiner at Laughlin AFB. He subsequently upgraded to the F-16A at MacDill AFB in 1988, and flew the F-16C at Hahn AB, Germany for two and half years. In December 1990, he deployed with the 10th Tactical Fighter Squadron to the United Arab Emirates and flew 45 combat missions in the F-16C during Operation Desert Storm. While deployed he was selected for the joint AFIT/TPS program. He entered the AFIT School of Engineering in September 1991 and in 1992 was elected to Tau Beta Pi. After completing formal course work at Wright-Patterson AFB, he began TPS in January 1993. Captain Taschner was a distinguished graduate of TPS Class 93A and was assigned to the F-16 Combined Test Force, Edwards AFB.

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13. ABSTRACT (Maximum 200 words)
This investigation examines the suitability of conventional, rate command/attitude hold (RCAH), and attitude command attitude hold (ACAH) response-types for the probe and drogue air refueling task. Data from a 1974 Calspan handling qualities investigation involving conventional response-types in the probe and drogue air refueling task were analyzed using the Bandwidth and STI Dropback criterions. Flight control laws were developed to achieve twelve superaugmented and two conventional configurations. The NT-33A analog variable stability system was used to simulate a relaxed static stability fighter and the NT-33A programmable digital flight control computer simulated the desired response-types. The handling qualities of the fourteen configurations were evaluated during eight flight test sorties. Data consisted of pilot commentary, handling qualities ratings using the Cooper-Harper rating scale, pilot induced oscillation tendency ratings, and turbulence ratings. The Bandwidth criterion supplemented with frequency response based control sensitivity metrics successfully correlated the observed handling qualities. Configurations with handling qualities deficiencies were characterized by any one of the following: excessive gain at the pitch and flight path bandwidths, excessive phase delay, low bandwidth, or a gain margin limited pitch attitude bandwidth.

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